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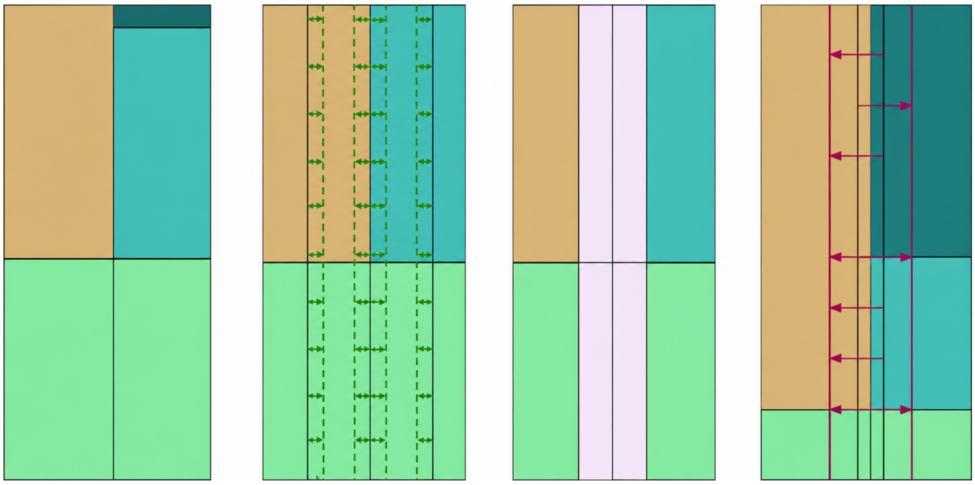

Displacements of buried pipelines due to sheet pile extraction in soft clay

A study on pipeline displacement using numerical modelling

Master's thesis in Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: A visualization showing four methods of numerically modelling sheet pile extraction.

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Abstract

Large parts of the Gothenburg region consist of soft and sensitive soils, making the ground prone to settlements when ground conditions are altered. Such changes commonly occur during installation and replacement of water and wastewater pipelines. These projects are often considered as a low-budget project, which often results in insufficient geotechnical investigations and measurements, and have in many cases led to disputes and expensive settlements following soil deformations. Pipeline installation is often carried out in trenches supported by retaining walls, often sheet pile walls, and while settlements caused by the unloading and reloading during excavation are relatively well understood, available studies on the effects of the sheet pile extraction remain scarce.

The aim of this study is to investigate how sheet pile extraction influences soil deformations, how the void created from the sheet pile is filled and further enlighten that sheet pile extraction can cause significant pipeline settlements in soft clay. The work was carried out by using numerical modelling in PLAXIS 2D together with comparison with a previously conducted full-scale field test in the Gothenburg region.

The numerical model in PLAXIS 2D was calibrated against observed horizontal and vertical displacements of the full-scale field test for the initial phases leading up to the sheet pile extraction, in order to capture the soil behaviour. Thereafter, different modelling approaches for simulating sheet pile extraction in PLAXIS were evaluated based on their ability to reproduce the observed horizontal displacements. The selected method, where low stiffness- and strength- parameters are applied to the soil surrounding the sheet pile, was then used to simulate the vertical settlements induced by the sheet pile extraction.

The results show that the numerical model was able to reproduce the general soil behaviour for all phases during pipeline construction. Furthermore, the results indicate that the majority of settlements originate from reloading the excavation with heavier material, but that the extraction of the sheet pile contributes to considerable settlements that should be taken into consideration. Lastly, this study contributes to an improved understanding of the additional settlements induced by sheet pile extraction in soft soils, although further and more extensive research is still considered necessary.

Keywords: Sheet pile extraction, Pipeline settlement, Soft clay, Soil deformation, Numerical modelling, PLAXIS 2D, Soil-structure interaction, Finite element analysis, Trench excavation

Displacements of Buried Pipelines Due to Sheet Pile Extraction in Soft Clay
A study on Pipeline Displacement Using Numerical Modelling
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Sammanfattning

Stora delar utav Göteborgsregionen består av lös lera, vilket gör marken känslig för sättningar när markförhållandena förändras. Sådana förändringar uppstår vid byggnation av vatten- och avloppsledningar. Dessa projekt betraktas ofta som lågbudgetprojekt, vilket många gånger leder till otillräckliga geotekniska undersökningar och har i många fall lett till tvister och kostsamma uppgörelser efter uppkomna markdeformationer. Installation av ledningar utgörs ofta i schakter med stödkonstruktion, ofta spontvägg, och medan sättningar orsakade av avlastning och pålastning är relativt väl förstådda, är tillgängliga studier kring effekterna av spontdragning fortfarande begränsade.

Syftet med denna studie är att undersöka hur spontdragning påverkar markdeformationer, hur hålrummet som uppstår vid spontdragning återfylls, samt att ytterligare belysa att spontdragning kan orsaka omfattande ledningssättningar i lös lera. Arbetet genomfördes med hjälp av numerisk modellering i PLAXIS 2D tillsammans med jämförelser mot ett tidigare utfört fullskaleförsök i Göteborgsregionen.

Den numeriska modellen i PLAXIS 2D kalibrerades mot observerade horisontella och vertikala förskjutningar från de inledande faserna av fullskaleförsöket fram till spontdragningen. Detta gjordes för att fånga jordens beteende. Därefter utvärderades olika modelleringsmetoder för att simulera spontdragning i PLAXIS baserat på deras förmåga att återskapa de observerade horisontella förskjutningar. Den valda metoden, där styvhet- och skjuvhållfasthets-parametrar är reducerade på jorden kring sponten, användes sedan för att simulera de vertikala sättningarna som orsakades av spontdragningen.

Resultaten visar att den numeriska modellen kunde återskapa det generella jordbeteendet för samtliga faser under ledningsinstallationen. Resultaten indikerar vidare att majoriteten av sättningarna uppstår till följd av återfyllning med tyngre material, men att spontdragningen också bidrar till betydande sättningar som bör tas i beaktande vid ledningsbyggnad. Slutligen bidrar denna studie till en förbättrad förståelse för de sättningar som följer av spontdragning i lösa leror, även om ytterligare och mer omfattande forskning fortfarande bedöms vara nödvändig.

Nyckelord: Spontdragning, Ledningssättning, Lös lera, Markdeformationer, Numerisk modellering, PLAXIS 2D, Jord-strukturinteraktion, Finita elementanalyser, Ledningsschakt

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Edvin Pettersson, Gothenburg, June 2026
Teodor Godenius, Gothenburg, June 2026

List of acronyms

Acronyms used in the report is listed below.

CRS	Constant Rate of Strain
DSS	Direct Simple Shear
FEM	Finite Element Method
GWT	Ground water table
HS	Hardening Soil
LE	Linear Elastic
MC	Mohr-Coulomb
MCC	Modified Cam-Clay
NC	Normally Consolidated
OC	Overconsolidated
OCR	Overconsolidation Ratio
POP	Pre Overburden Pressure
SS	Soft Soil

List of nomenclature

Nomenclature used in the report is listed below.

Roman lower case letters

c'	Effective cohesion
c_u	Undrained shear strength
u	Pore water pressure
w_L	Fall cone liquid limit
w_n	Natural water content
z	Depth from soil surface

Roman upper case letters

C_c	Compression index
C_s	Swelling index
E	Elastic modulus (Young's modulus)
E^{ref}	Reference stiffness modulus at reference stress
E_{50}	Secant modulus in deviatoric loading
E_{oed}	Secant modulus in one-dimensional compression
E_{ur}	Tangent modulus in unloading and reloading
K_0	Coefficient of earth pressure at rest
M_L	Constrained modulus from one-dimensional loading test

Greek letters

γ'	Effective unit weight
γ_{dry}	Dry unit weight
γ_{sat}	Saturated unit weight
γ_{unsat}	Unsaturated unit weight
γ_w	Water unit weight
η	Stress ratio
κ^*	Modified swelling index
λ^*	Modified compression index
ν	Poisson's ratio
σ'_c	Preconsolidation pressure
σ'_h	Effective horizontal stress
σ'_v	Effective vertical stress
σ_v	Total vertical stress
ϕ'	Effective friction angle
ψ'	Dilatancy angle

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1

Introduction

This chapter aims to provide a background to the problem, present the aim of the study, outline the structure of the report and describe the limitations of the study.

1.1 Background

Large parts of the Gothenburg region are characterised by soft clays that are highly compressible and sensitive to disturbances. These soil conditions can make the ground prone to settlements and displacements during the installation of new water and wastewater infrastructure. The challenging soil environment in Gothenburg not only poses problems for the installation but also for uncertainties regarding its long-term performance.

Pipeline construction and maintenance are often treated as low-budget projects, which may result in insufficient geotechnical investigations. Consequently, settlements and soil deformations may occur, potentially leading to disputes and considerable economic consequences. In urban areas with soft and sensitive soils, pipe installation is commonly carried out in excavated trenches supported by retaining walls, owing to space constraints and the requirements for lateral soil support to ensure stability (Franzén et al., 1999). This approach often results in significant settlements (Hultin & Reckman, 2024).

During pipeline construction in excavated trenches with retaining walls, there are different reasons why the pipeline may be subject to displacements (Oung & Brassinga, 2009). The main reason why pipelines settle is usually that the excavation is backfilled, and often with heavier material than the original material. Other reasons include installation effects, excavation bottom disturbances, changes in groundwater conditions, or sheet pile extraction. Among these, the latter has received limited research attention, and available studies of the impact remain scarce.

To improve the understanding of how sheet pile extraction influences pipeline settlements, this study compares results from a full-scale test reported in *Spontens inverkan vid ledningsläggning i lös lera* by Franzen & Spetz (1998) with numerical modeling. The study aims to provide further insights into how sheet pile extraction impacts pipeline settlements in soft clay. By improving the knowledge of the settlement mechanism on pipelines, costly damage and necessary maintenance measures can be avoided.

1.2 Aim

The aim of this study is to investigate soil behaviour during sheet pile extraction through various numerical modelling methods, and assess how the induced soil displacements affect pipeline settlements.

This report aims to answer the following questions:

1. "Which of the evaluated numerical modelling approaches in PLAXIS 2D is most suitable for accurately simulating the horizontal displacements in the surrounding soil induced by sheet pile extraction?"

2. "How does sheet pile extraction impact vertical ground settlements, and to what extent can numerical modelling approaches capture and predict these effects?

3. "How is the cavity created by sheet pile extraction closed, and what is the primary displacement pattern?

1.3 Limitations

This study is limited to soil displacements caused by loading and unloading processes and sheet pile extraction during soft soil excavations. The study acknowledges that other factors may influence soil deformations, but have not been included in the analysis. Factors not analysed include disturbances caused by sheet pile installation procedures, workmanship, excavation bottom disturbances, vibration effects, groundwater variations and simplifications related to the FEM model boundaries among others.

Furthermore, the analysis is based on several assumptions, due to limited information provided in the Franzen & Spetz (1998) field test and from assumptions made in the soil models. Soil is a complex and often non-linear material, whereas soil models and numerical calculations require idealization regarding behaviour. As a result, the numerical model may not fully capture the soil displacements that occur in reality.

Finally, the study only considers a limited number of parameter combinations and scenarios. Although the study tries to identify the most suitable method for comparing displacements associated with sheet pile extraction, it acknowledges that not every method can be evaluated. Therefore, there is a risk that other not evaluated methods provide better and more accurate representations of the observed ground behaviour from the full-scale field test.

1.4 Project outline

The study begins with a literature review covering geotechnical theory related to the study including stress redistribution, loading and unloading behaviour, earth pressures, soil deformations caused by sheet pile extraction and settlements induced by the extraction of the sheet pile wall. The literature review also introduces the numerical modelling theory and constitutive soil models used in the numerical modelling program, PLAXIS 2D.

Following the literature review and theoretical framework, a previously performed full-scale field test from the Gothenburg region is analysed in order to establish the necessary geological conditions and soil parameters for the numerical modelling.

Based on the reference full-scale field test, a numerical model was then developed in PLAXIS 2D. The numerical results are subsequently analysed and compared with the observed displacements in the full-scale test. Lastly, the results are discussed with regard to soil behaviour, settlements, modelling uncertainties, and the influence that sheet pile extraction has on pipeline settlement.

2

Geotechnical Theory

This chapter presents the theoretical framework that forms the geotechnical basis for this report. The effect of sheet piling in regard to its installation and extraction is presented here. Additionally, the chapter introduces numerical modelling concepts and constitutive models used in PLAXIS 2D, thus providing the foundation for the numerical model presented later in the report.

2.1 Sheet piling

Sheet pile installation and extraction are processes that alter the in-situ stress conditions in the surrounding ground and may induce both vertical and horizontal soil displacements. The magnitude and extent of these displacements depend on the method used for installation and extraction, soil type, groundwater conditions and vibration characteristics. Since sheet piles are commonly installed using displacement methods, the surrounding soil is subjected to stress redistribution, cyclic loading, and changes in pore pressure conditions.

The installation of sheet piles is commonly carried out using a vibratory hammer, impact hammer, or hydraulic jocking (Federal Highway Administration, 2008). The vibratory hammer induces vibrations into the soil, which temporarily reduce the friction and shear resistance between the sheet pile and the surrounding soil. This procedure causes the soil to behave in a fluidized manner, thereby easing the installation process. The impact hammer performs the installation by repeatedly lifting and dropping weights in order to generate impact force. Lastly, hydraulic jocking performs the installation by continuously applying a static force using hydraulic jacks (Das & Sivakugan, 2019).

2.1.1 Soil displacements from sheet pile installation

The installation effects on the ground differ between the installation methods. Generally, installations of sheet piles can be considered to be a displacement process, as soil is pushed away laterally, thus increasing the horizontal stresses towards the sheet pile (Bowles, 1996). Hence, the initial at-rest conditions are disturbed. In cohesive soils in undrained conditions, excess pore pressure is generated (Craig, 2004). Particularly in soft soil, it has been observed that horizontal soil displacements occur during the installation process of sheet piles, before an excavation takes place (Dapena et al., 2001).

When ground vibrations reach the soil from the vibratory hammer machine, the clay particles are subjected to cyclic loading and temporarily loses some of its strength and stiffness, as the vibration propagates through the ground as waves. This movement, as waves, causes deformations to the soil and also transfers energy to the ground, which may result in rearrangement of the soil particles and can also lead to densification of soil particles and, as a result, cause settlements (Deckner, 2013). The largest displacements of soil typically occur close to the installed sheet pile, where stress concentrations and vibration amplitudes are the highest. The deformations generally decrease with distance from the sheet pile.

2.1.2 Soil displacements from sheet pile extraction

The extraction of sheet piles from the ground after a trench is refilled can induce settlements and lateral displacements in the surrounding ground due to changes in stress conditions and vibration during extraction. Research by Meijers & Tol (2002) found numerous forms of damage associated with vibratory sheet pile extraction, including uneven settlements, horizontal ground displacements, and instability caused by excess pore pressures. Cyclic loading of the soil during the extraction disturbs the soil structure that surrounds the extracted sheet pile, reducing the adhesion between the clay and sheet pile surface.

Also observed by Meijers & Tol is that a temporary void is left behind after the sheet pile extraction. As the sheet pile itself has a volume to it, there will be subsequent movement of the surrounding soil to fill the void upon its extraction. In advanced settlement predictions for excavations that include sheet pile extraction, such as that of Oung & Brassinga (2009), it is explicitly mentioned that the volume loss should be accounted for. As the cavity generated from the sheet pile extraction can not remain open under in-situ stress conditions and must be closed.

Testing by Meijers & Tol showed that the largest displacements occurred adjacent to the top of the pile as the soil at the surface temporarily loses strength and stiffness. These displacements then decreased with depth and horizontal distance. Soil-structure interaction and adhesion may develop between soil and sheet pile surfaces, especially in fine-grained soils where cohesion will contribute to attachment behaviour (Craig, 2004). This means that the void left by the extracted sheet pile may have a larger volume than that of the pile, if such behaviour occurs, and soil stuck to the surface is extracted along with the sheet pile. This would thus enhance the horizontal inwards movements of the soils surrounding the void.

Highlighted by Dapena et al. (2001) is the influence of the refill material on the specific deformation behaviour. For an excavation backfilled with uncompacted coarse material, the movement of the soil is likely accommodated through the compression and rearrangement of the refill material itself. This indicates that the void left from the sheet pile extraction can be filled partly by the movement of the surrounding retained soil and partly through the internal deformation of the backfill adjacent to the void. However, this is highly dependent on the properties of the surrounding soil and the backfill. A soft clay is expected to displace and fill the void significantly more than the backfill material than a coarser material would. A backfill using material similar to that of the excavated soil can be expected to govern a different behaviour and deformation, where the void is filled from both sides.

2.2 Numerical modelling

Numerical modelling is widely used in geotechnical engineering as a tool to analyse soil behaviour, which is too complex to be analysed using analytical methods alone (Seequent, 2025a). The finite element method (FEM) provides a framework for solving such problems. With this, a matrix of the soil domain is created, where conditions for individual elements in the soil are calculated. PLAXIS 2D is a finite element software developed for such geotechnical engineering purposes. The program allows users to define complex geometries, apply loads and boundary conditions, and simulate soil behaviour over different construction stages. The response of each element in the soil is calculated, enabling the software to predict soil deformation and structural response for the entire model. PLAXIS also incorporates groundwater modelling, allowing for coupled analysis of mechanical behaviour and pore pressure together.

2.2.1 Constitutive soil models

A key aspect of numerical modelling in PLAXIS is the choice of an appropriate soil material model (Karstunen & Amavasai, 2017). Various models exist within the software, using different parameters and calculation methods for problems. Soil type, loading conditions, and the accuracy of the desired outcome must hence be considered when deciding which model to use. The models are of varying complexity and realism. A simpler model, whilst it might produce a less accurate result, requires fewer parameters and hence less work to produce a deformation prediction. The availability of multiple constitutive models in PLAXIS provides flexibility for the user, where a model can be chosen to best represent the expected soil response. The characteristics of the constitutive models used in this study are presented in the following section.

Linear elastic model

The Linear Elastic (LE) model is the simplest constitutive soil model available in PLAXIS. The model assumes that the soil behaves as an isotropic, homogeneous, and perfectly elastic material (Seequent, 2025a). With perfect elasticity, the model assumes that the relationship between stress and strain is fully linear. The full linearity means that there exists no plasticity in the model. Thus, all deformations are fully reversible, and no failure predictions are provided from the material model.

The LE model uses the basic elastic stiffness parameters Young modulus, E, and Poisson's ratio, ν (Seequent, 2025a). The Young modulus describes the stiffness of the material and governs the deformations of the material under high stresses. The Poisson ratio describes the ratio between axial and lateral strains during the loading phases.

This model is generally not suitable for the modelling of soil behaviour, as real soils exhibit stress-dependent behaviour, non-linear responses, and irreversible deformations as strain levels increase. The model does not include plasticity, stress path dependency or stress history effects, all of which are important for a realistic soil response. Its application can be said to be limited to preliminary and simplified analyses. Hence, the LE model is rather limited in the purpose of modelling excavations. With its limitations, it would affect the resulting sheet pile deflections, stress redistribution and the development of plastic zones.

Mohr-Coulomb model

The Mohr-Coulomb (MC) model is implemented as a linear elastic, perfectly plastic material model (Seequent, 2025a), combining linear elasticity with a predefined failure criterion. Here, the model assumes that the soil behaves elastically until a failure condition is reached, defined by the MC failure criterion. After this point, plastic deformations occur without any further increase in stress. Due to its simplicity and limited number of parameters, the MC model is often used as a first approximation of soil behaviour in engineering analyses.

The stiffness in the MC model is defined through the same parameters as in the LE model, with Young's modulus, E, and Poisson's ratio, ν (Seequent, 2025a). Together, these two parameters describe the soil stiffness and control the relationship between stress and strain before yielding occurs. In addition to the stiffness parameters, the MC-model adds three parameters that govern the plastic behaviour of the soil (Seequent, 2025a). These parameters are effective cohesion, c', the effective friction angle, ϕ', and the dilatancy angle, ψ'. These three parameters determine the strength of the soil.

The MC model provides reasonable predictions of soil strength and can give predictions of failure mechanisms in simple cases. It is hence widely used for preliminary analyses and stability assessments. However, the model has several important limitations when applied to more advanced and realistic soil problems. The assumption of constant stiffness leads to inaccurate deformation predictions, as real soils exhibit stress-dependent stiffness.

Hardening soil model

The Hardening Soil (HS) model is a constitutive model that better captures the behaviour of soil than the simpler LE and MC models. It is an elasto-plastic model which incorporates stress-dependent stiffness and plastic hardening, making it suitable for the modelling of more complex problems, such as excavations and embankments (Seequent, 2025a). Unlike the MC model, the HS model distinguishes between different types of loading and accounts for the non-linear behaviour of soils, particularly the increase in stiffness with increasing stress.

Soil behaviour in the HS model is described using a non-linear stress-strain relationship combined with plastic hardening. A key feature is the use of a hyperbolic stress-strain curve, which allows the stiffness to decrease with increasing strain, thus reflecting the true behaviour of the soil better (Seequent, 2025a). The distinction between the various loading and unloading conditions is captured through three stiffness moduli: The secant stiffness in primary deviatoric loading, E_{50}^{ref}, the secant stiffness in primary one-dimensional compression, E_{oed}^{ref}, and the tangent stiffness in unloading and reloading, E_{ur}^{ref}. The HS model uses the MC failure criterion to describe the soil strength at failure (Karstunen & Amavasai, 2017). While stiffness is nonlinear and stress-dependent, the shear strength is controlled by a fixed failure envelope. Soil strength is hence characterised by the same three parameters as the MC model, the effective friction angle ϕ', the effective cohesion c', and the dilatancy angle ψ'.

With the material model capturing the hardening of the soil, it drastically improves on the simpler models in terms of deformations in the context of an excavation. Through the increase of soil strength as plastic strains develop, the HS model better represents soil behaviour than the simpler strength prediction in the previous models. Shear hardening and compression hardening, mainly controlled to E_{50} and E_{oed} respectively, help in the predictions of the sheet pile movement and soil settlements.

Soft soil model

The soft soil (SS) model is developed for highly compressible soils. The material model is based on the concepts derived from critical state soil mechanics, and is inspired by the Modified Cam-Clay (MCC) model, although with modifications that distinguish it from a strict critical state formulation (Karstunen & Amavasai, 2017). The SS model is formulated in terms of effective stresses and is intended to represent soil behaviour under general stress paths. This, unlike simpler models, is essential in geotechnical applications as soil exhibits different behaviour under loading and unloading, which can not be described with simple one-dimensional assumptions.

The soil behaviour of the model is described with an elasto-plastic framework with stress-dependent stiffness and irreversible plastic deformations (Seequent, 2025a). In contrast to simpler models, such as the LE and MC models, the non-linear behaviour of the soil during compression is accounted for. Rather than a constant stiffness, it varies with the effective stress levels, meaning an increase in effective stress results in an increase in stiffness, thus reflecting the behaviour of real soils better.

The SS model uses different types of stiffness parameters compared to the previously presented constitutive models, namely λ^* and κ^*, where the former is the modified compression index and the latter is the modified swelling index. The parameters describe the slope of the virgin compression line and unloading/reloading line in logarithmic stress space. Strength of the soil is, similarly to previously introduced models, defined through the effective cohesion c', the effective friction angle ϕ', and the dilatancy angle ψ.

The model captures a more realistic representation of soil behaviour of soil due to its logarithmic stress-strain relationship and stress dependent stiffness, thus capturing the non-linear compressibility of the soil (Seequent, 2025a). An advantage of the SS model is its ability to represent complex volumetric behaviour in soft soils. With the incorporation of plastic hardening through volumetric strain, the model can simulate the behaviour of primary consolidation and stress history through OCR or POP. Despite its many upsides, the SS model is more limited than certain other models in the consideration of complex stress paths in unloading and shear. For an excavation case, the stiffness may be underestimated, and stress redistribution around the excavation can be misrepresented.

2.2.2 Sheet pile extraction modelling methods

The extraction of a retaining structure in finite element analyses can be difficult to represent accurately using simple deactivation procedures alone. In PLAXIS, deactivating a sheet pile removes its structural stiffness and interaction with surrounding soil, which then results in a stress redistribution and subsequent soil displacements (Seequent, 2025c). Whilst this procedure captures the general unloading mechanism associated with sheet pile extraction, the resulting soil movement can be underestimated compared to observed field behaviour. A significant limitation with the direct deactivation approach is that the numerical model may not fully reproduce the stress release and volume change effects associated with the actual extraction phase. As presented in Chapter 2.1.2, the extraction of the sheet pile disturbs the surrounding soil and creates additional displacements through compaction of the surrounding soil and the physical cavity left from the sheet pile. This is not inherently captured through the structural deactivation alone. The calculated displacement may become limited in magnitude due to this, particularly close to the extracted sheet pile wall.

To improve the representation of the extraction process, additional modelling approaches can, therefore, be used to alter the model response to the extraction of the sheet pile and better approximate the subsequent ground movement. The following section presents different approaches investigated in this study.

Imposed volumetric strain

Volumetric strain is a fundamental phenomenon in geotechnical analysis, describing the volumetric change of a soil body under loading, unloading, or stress redistribution. In numerical modelling, volumetric strain is associated with the compression or expansion of the soil skeleton and is related to changes in the effective stress conditions. Excavation processes, loading, unloading, and cavity closure are examples of mechanisms that may introduce volumetric changes in the soil mass. In PLAXIS, volumetric strain can be directly imposed by the user, allowing a volumetric change to be artificially added to a soil, either expanding or contracting said soil.

In PLAXIS, this is represented by the volumetric strain option, which allows the user to increase or decrease the volume of a soil by adding strains in the different directions (Seequent, 2025b). A positive strain input corresponds to an increase in volume, whereas negative input values lead to contraction. During the calculation process, PLAXIS automatically maintains equilibrium in the output by adjusting the stresses and forces in both the soil mass and the surrounding soil. Therefore, it is essential to consider the interaction between the soil stiffness and volume expansion or volume contraction, as this relationship influences the effectiveness of the imposed volumetric change.

The displacement response of the imposed volumetric strain is highly dependent on its surrounding soil and its stiffness. A stiffer surrounding soil provides a greater resistance to the imposed displacements, whereas a softer soil deforms more easily, allowing for larger deformations. The response of the model to the volumetric strain is hence not solely dependent on the magnitude of the strain, but also on the surrounding soil, its stress state, and stiffness conditions. In excavations in soft clay, the redistribution of stresses that occurs may result in significant deformations even for small imposed volumetric strains.

The use of the imposed volumetric strain is useful in situations when a physical process cannot be fully represented through conventional staged construction procedures alone. By introducing a controlled expansion or contraction in specific areas, additional deformations can be approximated without altering the entire model geometry. The use of imposed volumetric strain, however, should be done in a manner that is representative of real soil behaviour (Seequent, 2025b). The deformations should reflect actual deformations of a studied problem and not excessively large or physically unrealistic strains. Hence, careful consideration of its implementations needs to be taken.

Soil cluster

Creating an unsupported void, the width and depth of the cavity left in place of the extracted sheet pile in PLAXIS will likely result in an error within the program. Instead, this void can be represented with a soil cluster with modified material properties. With this method, the finite element mesh is maintained throughout the staged construction analysis, whilst also approximating the mechanical behaviour of an empty cavity. A cluster of this sort, with strongly reduced stiffness properties, helps the simulation of temporarily excavated volumes where numerical stability and convergence may otherwise become difficult to achieve during calculation (Seequent, 2025c).

Although the cluster remains present in the mesh, its influence on the surrounding soil response is minimised through the reduction of its mechanical parameters. The stiffness parameters are assigned very low values in order to minimise the resistance of the cluster. By lowering the stiffness, the cluster contributes minimally to the global stiffness matrix, allowing the surrounding soil to deform in a manner more representative of an actual sheet pile extraction where a cavity is to be filled. If a more regular stiffness is assigned to the cluster, it provides greater support to the adjacent soil, resulting in an underestimated displacement and an unrealistic stress distribution. The reduction of stiffness in the cluster material is therefore essential for reproducing the behaviour associated with sheet pile extraction processes.

In addition to the stiffness, the unit weight of the material used in the soil cluster is reduced to a negligible value. This is necessary to minimise the gravitational force of the material. An actual void would not contribute to any self-weight on the directly underlying soil. Assigning a unit weight similar to that of the surrounding soil would hence produce an unrealistic vertical stress distribution within the model.

The shear strength parameters of the cluster material are also reduced in order to limit the transfer of shear stress through the excavated region. If the cluster retained realistic strength properties, it could continue to behave as a stable load-bearing material despite its reduced stiffness, thereby influencing the calculated stability and deformation behaviour of the excavation during the sheet pile extraction phase (Seequent, 2025c). However, the strength parameters ϕ' and c' should not be reduced to zero, as strength at this level may result in numerical instability and excessive element distortion during the calculation. Instead, small non-zero values are assigned to the material to maintain stable calculation conditions whilst also ensuring representative behaviour of the cluster, similar to that of a void.

The method of using a severely weakened cluster to represent the void created for the sheet pile extraction therefore, allows the surrounding soil to behave as if a cavity exists in place of the extracted sheet pile, whilst not disturbing the finite element calculations during the construction stages. This increases the robustness of the staged construction analysis and reduces convergence issues associated with the sudden removal of soil elements in the numerical model.

Prescribed line displacement

Prescribed line displacement is a function in PLAXIS that allows the user to manually displace any given structure or soil mass within the model. By adding a prescribed line displacement, the object will displace the prescribed amount (Seequent, 2025b). This helps the user to impose a displacement rather than being generated from external loads. This can be used to model controlled movement of soil or structures when the displacements are known beforehand.

Prescribed line displacements are activated through staged construction and are applied to the specific stage upon its activation. The magnitude of the displacement is defined by the user and can be made to be constant or vary along the geometric line (Seequent, 2025d). Thus, a known displacement profile can be recreated using a line with prescribed displacements that match those of the reference profile. When the displacement is activated in PLAXIS, the imposed movements are applied incrementally during the calculation phase, causing the surrounding soil to deform and redistribute stresses accordingly. The displacements thus develop progressively in the prescribed direction rather than occurring instantaneously. Displacements are expected to be largest close to the boundary of the prescribed displacement, and then decrease in magnitude with lateral distance. The response of the surrounding soil is largely dependent on the stiffness and constitutive model of said soil. Stiffer soils deform less compared to softer soils.

Application of the prescribed line displacements in numerical modelling can help model imposed ground behaviour associated with excavations, tunnel construction, structural deformations, or the emergence of voids or cavities. With this, objects and soils can be moved, causing gaps in the model without causing problems with cavities in the mesh. Thus, numerical stability can be maintained as long as no displacements unreasonably large relative to the model are prescribed. However, as the prescribed displacements are directly controlled by the user rather than naturally generated through stress redistribution, the calculated response and its reliability are strongly dependent on correct user input (Potts & Zdravković, 1999).

3

Reference full-scale field test

This chapter presents the full-scale field conducted by Franzen & Spetz (1998), which forms the basis for the numerical modelling in this study. Here, the geological and geotechnical conditions are presented together with the field investigation, laboratory testing, instrumentation as well as the results from the full-scale test.

3.1 Background and objectives of the full-scale field test

The Franzen & Spetz (1998) field test investigates the influence of sheet piles during excavations in soft clays. The objective of the project was to study the horizontal ground displacements associated with excavations, backfilling, and sheet pile extraction. Pipelines commonly experience displacements after the trench is refilled and the sheet pile is extracted. The project had the aim to investigate how these displacements vary with varying sheet pile dimensions, sheet pile material types, and times of extraction. Through various measurements, the magnitude and distribution of displacements were measured at various stages of the excavation process. The excavation itself is a 30m long trench supported by sheet piles divided into sections of varying retention conditions. The different sections of the trench are shown in Figure 3.1 with their respective notations.

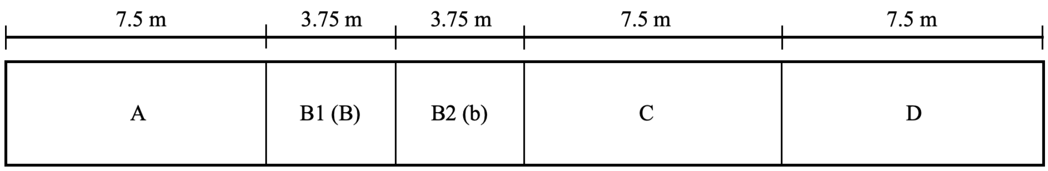

Figure 3.1: Sections of the trench with their lettered notations, including alternative reference letter in parentheses.

In this study, only section B2 and D are of interest. Section B2 (also later referred to as section *b*) is considered the normal section, with a regular sheet pile and a 2 m embedment depth. For section D, the sheet piles were exchanged for wooden piles with the same dimensions as the regular sheet pile. The trench itself measures 2 m in width and 3 m in depth. The pipeline installed at the bottom of the trench is laid atop a 70 mm thick concrete slab, and measures 300 mm in outer diameter.

3.2 Geographical and geological conditions

The field test was carried out in Mölndal, just south of Gothenburg, at the end of the 1990s. There is a significant presence of soft clay in this specific area of Sweden, making it an interesting case to consider for this type of problem. The stratigraphy, as determined from field investigations, is shown in Figure 3.2.

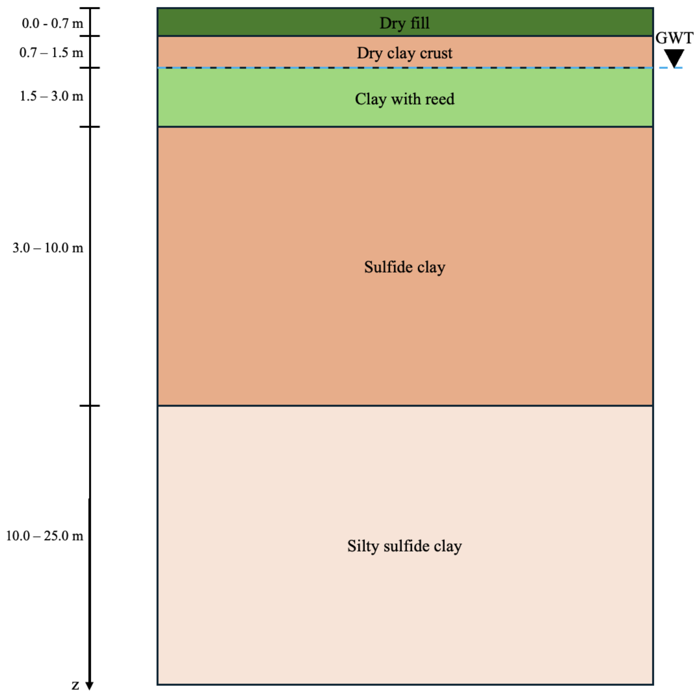

Figure 3.2: Stratigraphy found at the spot for the full-scale test.

As the figure shows, five primary layers are identified. A thin layer of dry fill is followed by a thin layer of dry clay crust. Following this is 25 to 30 m of clay with properties, particle size, and organic content varying with depth. Three primary layers are identified within the depth of the clay. The groundwater table is located at a depth of 1.5 m beneath the surface level, with hydrostatic conditions down to a depth of at least 5 m.

3.3 Field and laboratory investigations

The report covers a full-scale field test. Investigations in the full-scale test were divided into two categories. Firstly, tests were conducted to determine the mechanical properties of the soil. Secondly, the excavations were instrumented in order to monitor soil displacements and pore pressure variations during the construction stages.

3.3.1 Soil investigation and sampling

Although existing measured samples and tests from the area were evaluated, additional samples and tests were taken and performed. The groundwater conditions were observed from field investigations. The strength of the soil was determined through laboratory testing and two vane shear tests. Two samples were taken with piston sampling and then tested in the laboratory. With piston sampling, the samples remain as undisturbed as possible, thus making the results from the consequential laboratory tests more representative.

3.3.2 Laboratory testing

In the laboratory, the samples were tested with standard investigation, determining soil classification and basic properties, before more advanced testing is performed. The samples are then tested with CRS-testing to determine compressibility and triaxial tests to determine shear strength and stress-strain behaviour. CRS-testing determines the one-dimensional consolidation properties of a sample at a constant stress rate. Triaxial testing loads a cylindrical test in three-dimensional stress conditions under confining pressure.

3.3.3 Field instrumentation and monitoring

Before, during, and after the excavation process, different measurement devices were placed at various places in and around the trench. The tools used for measuring were bellow-hose settlement gauges, inclinometers, surface settlement gauges, and piezometers. Their respective placements along the trench can be seen in Figure 3.3.

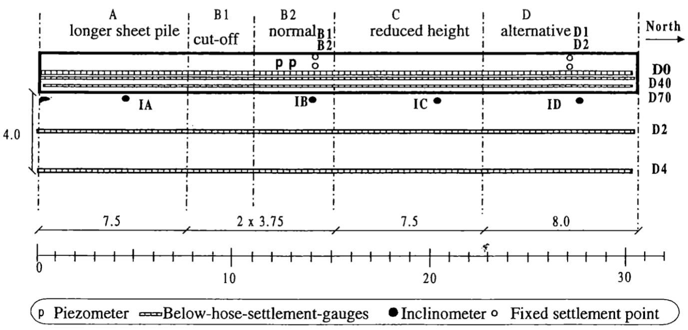

Figure 3.3: Instrumentation along the trench as seen from above.

The bellows-hose settlement gauges stretch across the length of the trench and can measure settlements of the base. Three gauges are installed at the base, one atop the pipeline, and two at distances of 40 and 70 cm respectively from the center of the pipe. Measurements are taken every meter along the hoses, meaning between 33 and 35 measuring points for each hose.

In order to measure the heave of the excavation bottom, four screwed-in settlement gauges were installed prior to the excavation taking place. In total, two pairs of two gauges were installed at a depth of 3.2 m. The respective pairs were installed at distances 0.25 and 0.75 m from the sheet pile wall of sections B2 and D, see Figure 3.3. The gauges were in the shape of screws and were put into place using an extension rod to get them to the correct depth.

The horizontal displacements of the sheet pile wall were measured using inclinometers. A 12 m deep hole was drilled 40 mm from all sections, a distance which would not disturb the soil displacements. In these holes, inclinometers were installed at the depths 1.5, 2.25, 3, 4, 5, 6, 8, and 11 m beyond the ground surface level.

3.4 Interpretation of soil parameters

Through field observations and laboratory testing, a stress profile over the effective stress and preconsolidation pressure was determined, as presented in Figure 3.4.

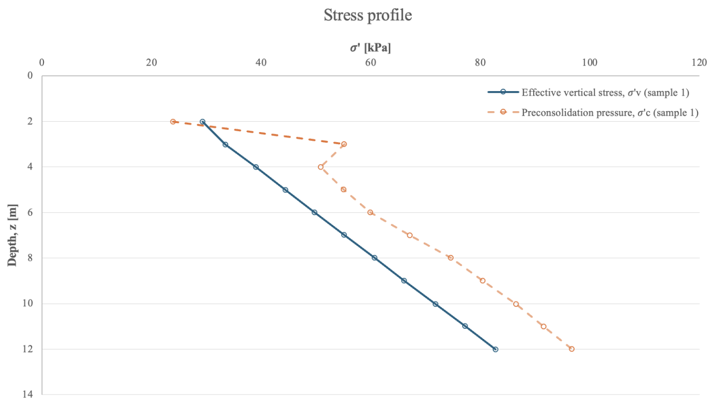

Figure 3.4: Stress profile of the soil at the excavation site.

From the stress profile, it can be seen that the soil is normally to slightly overconsolidated with a pre-overburden pressure (POP) of 10 to 15 kPa. The shear strength of the soil, being evaluated from different tests, was simplified to have one representative line, as seen in Figure 3.5.

The shear strength is said to be 10 kPa at the bottom of the unsaturated zone, increasing by 4.5 kPa/m down to 3 m depth. From this point, the strength increases with 0.35 kPa/m until 10 m, where it instead increases with 1.5 kPa/m.

Furthermore, the natural water content is said to vary between 65 and 110%, where the higher value represents the upper stratum. The fall cone liquid limit varies between 58 and 76%. It is also stated that the clay is highly sensitive down to a depth of 3.5 m, medium sensitive from 3.5 m to 15 m, and after that depth it once again is highly sensitive.

3.5 Construction sequence

The excavation is constructed in distinctive stages, which allows for more accurate measuring of soil displacements. Before the sheet piles were installed, the 0.7 m thick dry fill was excavated. Following this, the sheet piles were installed with a 2 m distance between them. During the excavation process, struts and ridge beams were installed at two levels

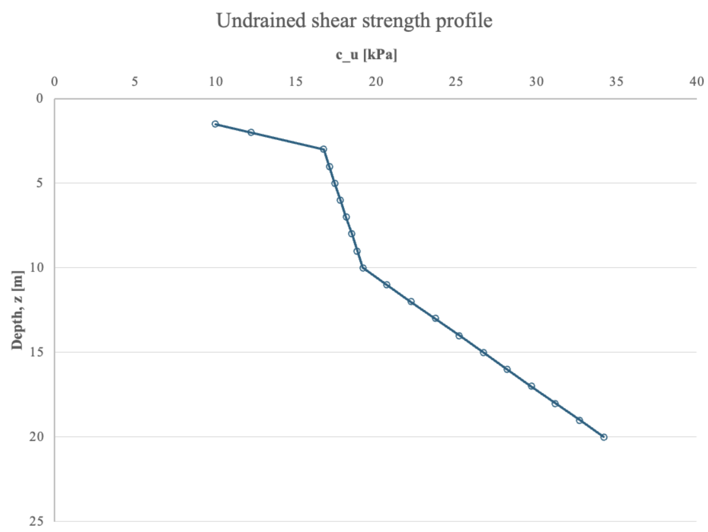

Figure 3.5: Shear strength profile of the soil at the excavation site.

to support the sheet piles. The top layer of struts and beams was placed at surface level, and the bottom layer was placed at 2 m depth in the trench. Once the desired depth was reached, a concrete slab with a thickness of 70 m was placed at the bottom of the excavation. With this, the pipeline could be installed. The pipes are 1 m long sections made of concrete, which measure 300 mm in diameter. The trench was then filled with coarse refilling material with the fraction sizes 0-18 mm, the first meter, upon which a coarser material with fractions between 0-60 mm was used to fill the trench up to the surface level. Before completely refilling, the lower level of struts and beams was removed. Once the trench was refilled, the sheet piles could be extracted from the ground. As mentioned in Chapter 3.3.3, various measuring tools were used for the field testing, many of which were installed before the trench was refilled.

3.6 Observed ground behaviour

The soil displacements during the excavation were measured for the different construction stages. Thus, the effect on the surrounding soil from each of the stages could be determined. The soil displacements were measured for each of the sections with varying support conditions. However, only the normal section B2, or *b* as several graphics refer to it, and D is considered of interest for this study. The settlements and heave on the excavation bottom were measured by the bellow-hose settlement gauges and screwed-in settlement gauges, the horizontal displacements of the sheet pile wall as measured by inclinometers and the pore pressure as measured by piezometers. Although the pore pressure is not considered for this study. The different soil displacements were measured for the different construction stages.

3.6.1 Horizontal sheet pile displacement

The horizontal displacements of the sheet pile were measured after the excavation stage, after the backfilling stage and after the extraction of the sheet pile, the results of which are seen in Figure 3.6. It should be noted that the considered section is missing from this graphic, and the section referred to as B is the one previously denoted as $B1$. How this is taken into consideration for the project is presented under Chapter 5.

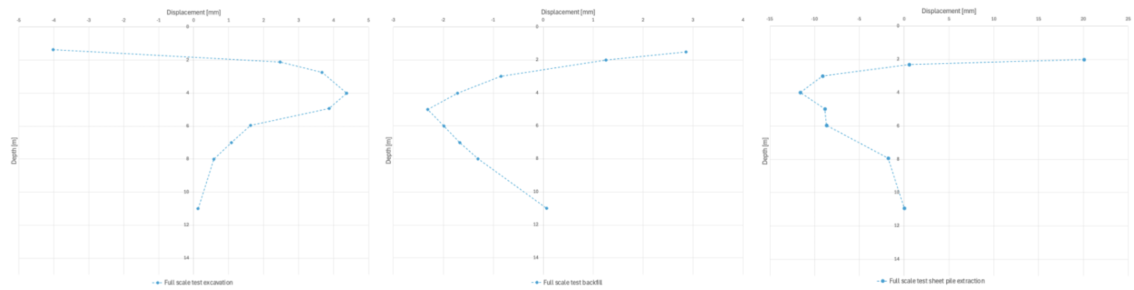

Figure 3.6: Measured horizontal displacement for the stages a) Excavation start, b) full refill, and c) pile extraction, for the sections A extra long, B cut off, C extracted at half refill, and D wooden piles.

Displacements for these stages are calculated according to Formula 3.1.

$$\Delta displacement = displacement\, stage_{i+1} - displacement\, stage_i \tag{3.1}$$

Thus, only the displacements for the specific stage are shown in the graphs. The different sections behave similarly until the sheet pile wall is extracted. At that stage, the horizontal displacements begin to differ between the sections.

3.6.2 Excavation bottom heave

With the settlement gauges being installed before the excavation taking place, the measuring of the soil displacements in the sections B2 and D at a depth of 3.2 m could start as the sheet pile was first installed. The heave following the excavation, marking the maximum level of the soil at the excavation bottom, is measured 10 to 15 mm in the gauge located 75 cm from the sheet pile. Disturbed measuring and missing measurements mean limited data is available to interpret for the heave.

3.6.3 Excavation bottom settlements

The settlements of the bottom of the excavation were measured for the refilling, divided into two separate stages, extraction of the sheet pile, as well as six separate time stages after the sheet pile extraction. The resulting settlements from the stages on the three separate settlement gauges are seen in Figure 3.7.

The different sections show similar settlements following the full refill stage, where the settlements are rather even along the excavation bottom. Upon sheet pile extraction, the center of the excavation bottom settles significantly more than the edges. This can be seen for all sections.

3.6.4 Further observations

Due to the location of the settlement gauges outside of the excavation being used as a working area with transports and similar, the resulting soil displacements from those were

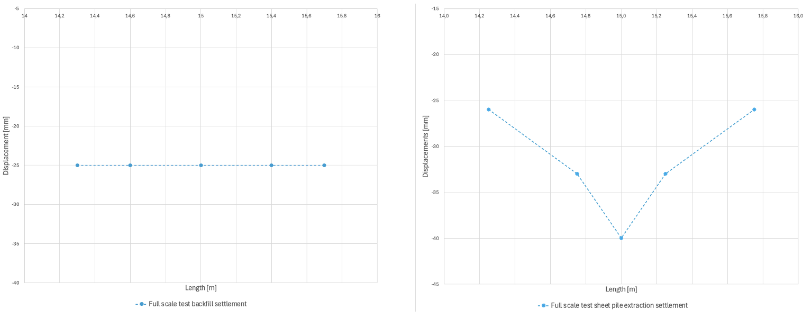

Figure 3.7: Total measured vertical settlements at a) full refill and b) sheet pile extraction. Measurements taken at the top of the pipe, 40 cm from the pipe center and 70 cm from the pipe center along the excavation bottom.

considered unreliable and are hence not part of the analysis. Only a very small amount of clay was found attached to the sheet piles installed separately to determine the extent of the clay adhesion during the sheet pile extraction. Although found to vary between 0 and 15 mm, with the dry crust excavated here in order not to contribute to scraping off clay, as well as there being a negligible amount of clay for most places on the sheet piles, it was chosen to be disregarded in the results and analysis in the report.

4

Methodology

This chapter presents the methodology used in this study, including literature review, the Franzen & Spetz (1998) full-scale field test description and interpretation, soil parameter determination and numerical modelling in PLAXIS 2D. An overview of the methodology is presented in Figure 4.1

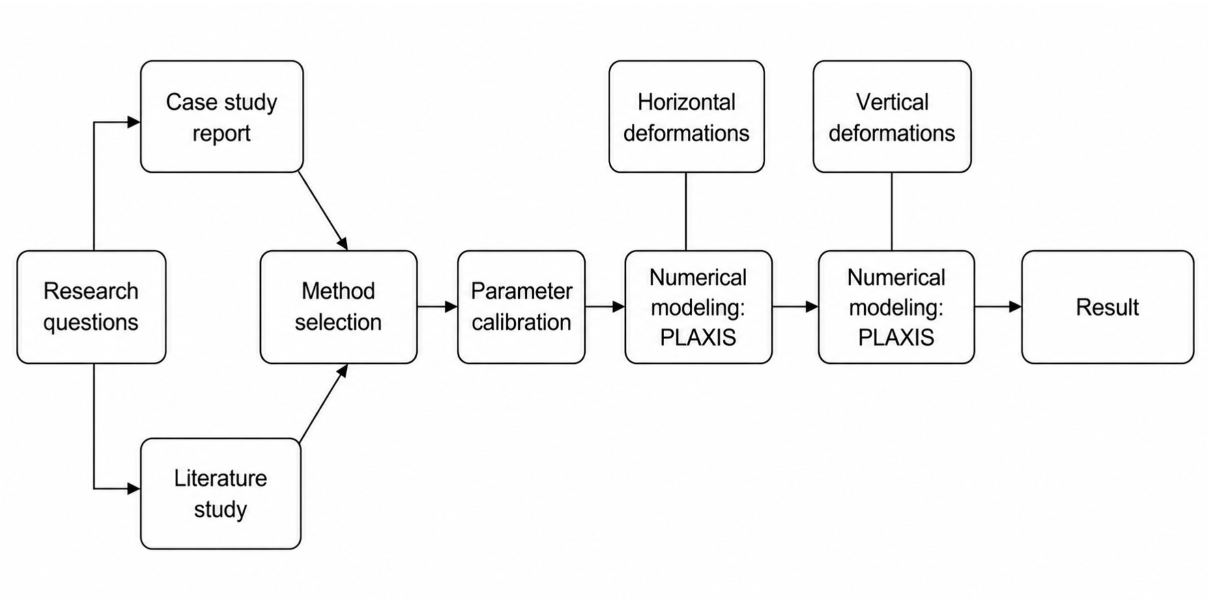

Figure 4.1: Methodology chart

4.1 Research approach

This study adopts a quantitative research approach, where literature review, analytical calculations, and numerical modelling are combined. The methodology behind the approach is to investigate soil displacements associated with sheet pile extraction. The finite element modelling is then used to evaluate the capability to reproduce the observed behaviour from the full-scale field test. The unloading and reloading stages are used to calibrate the model. This creates the research framework presented in Figure 4.1.

A literature review was conducted to establish a theoretical foundation to provide guidance and support for the selection of decisions throughout the study. The review focused on excavation induced soil deformations, sheet pile extraction induced soil displacements, numerical modelling practices, and constitutive soil model behaviours. Scientific journals, technical reports, and industry publications were revived using libraries and academic databases. The findings from those publications were used to guide the selection of soil models, input parameters, and modelling approaches.

Numerical modelling was selected as the primary analysis approach due to the need to analyse complex soil structures and geometry, and the non-linear behaviour of the soil. The stress distribution and soil behaviour associated with these processes are difficult to analyse using analytical methods alone. Using a numerical modelling approach, the study could reach a more suitable and accurate result regarding ground behaviour and soil deformations. Analytical methods were deemed insufficient for describing the ground behaviours studied for the overall behaviour, but were nevertheless used where established empirical relationships of soil parameters were evaluated.

The numerical modelling and numerical analyses were conducted using the FEM software PLAXIS 2D. The numerical modelling, including the selection of soil models, was developed in consultation with the project supervisor and project examiner. Input parameters were derived from site investigation data, the literature review, and engineering judgment. The input parameters were refined throughout the project through soil testing in PLAXIS and by comparing the observed behaviour in PLAXIS 2D with the observed ground behaviour in the full-scale field test for the unloading and reloading phase. This enabled the model to be calibrated before using it in a simulation of the sheet pile extraction.

4.2 Soil parameter determination

A challenge in the modelling of excavations is to capture the behaviour of the soil with regard to its stiffness and its previous loading conditions. This impacts the way displacements occur during the execution of the excavation. Hence, the initial state conditions and capturing stress dependent stiffness and the behaviour of the soil during the specific construction stages are essential. The following section presents how soil parameters have been determined. The values used in the numerical model is presented later, in Chapter 4.3.2.

4.2.1 Initial stress and hydraulic conditions

The initial conditions of the site are important to have defined correctly. Incorrect in-situ conditions will affect the other analyses that follow. The said conditions are explained in this section.

Initial stress state

The state of the soil before excavation is defined by its stress history, which is presented earlier, in Chapter 3.4. The POP is said to be 10-15 kPa for the clay layers. The OCR can be calculated for the different depths through the ratio between the pre-consolidation pressure and effective stress. With pre-consolidation pressures only known from a depth of 2 m, the OCR is assumed to be greater closer to the surface. Although testing suggests the pre-consolidation pressure is lower than the effective stress at the measurement taken at 2 m depth, this is not reasonable and is assumed to be a measuring error. The top clay layer is overconsolidated, and hence a POP greater than that of the underlying layers is assumed here.

Coefficient of earth pressure at rest, K_0

With the soil being characterised as normal- to overconsolidated, the in-situ stress state is influenced. The coefficient of earth pressure at rest, K_0, for a normally consolidated soil with $OCR = 1$ is calculated using only the effective friction angle ϕ'. In a state of overconsolidation, the OCR is also used for the calculation of K_0 through Equation 4.1

$$K_0 = (1 - sin\phi')\sqrt{OCR} \tag{4.1}$$

Strength parameters

Through Figure 3.5, the undrained shear strength, c_u, is determined for all clay layers. However, the drained strength parameters ϕ' and c' are initially assumed values before being iteratively tweaked, as presented in Chapter 4.3.2. The top clay layer is overconsolidated, whilst the two clay layers beneath are normally consolidated to lightly overconsolidated. The overconsolidated clay is assumed to have a higher cohesion than the other clay layers. Without reference values for undrained shear strength for the two dry layers and the coarse refill material, strength properties have been assumed based on the material description in the report covering the full-scale field test.

Unit weights and hydraulic conditions

In Figure 3.4, the effective stress measured in the full-scale field test is presented. There are hydrostatic conditions at a depth of 1.5 m. Although only known to be hydrostatic down to 5 m depth, the same conditions are assumed throughout the clay layers. Knowing the hydraulic conditions, a total stress can be determined from the effective stress. Calculating the difference in stress between different depths, a unit weight can be determined for the different layers in the stratigraphy. For the coarse backfill material, unit weights have been estimated based on its coarseness and then adjusted in the parameter calibration during the model verification process, presented in Chapter 5.1.1, to better replicate the settlements caused through the refill stage.

4.2.2 Constitutive model parameters

The various material models used to define the properties of the soils in the numerical model are defined with different parameters. How the parameters are derived is described in this section.

Mohr-Coulomb stiffness modulus

The Mohr-Coulomb material model is used for the two dry layers at the top of the soil. The reference report provides no information on the soil above the GWT. Thus, the stiffness in these two layers can only be estimated based on their description in the report covering the full-scale field test.

Hardening soil stiffness moduli

For the layers modeled with the HS material model, the stiffness parameters in primary deviatoric loading, one-dimensional compression, and unloading and reloading are required. As this material model is only used for the coarse refill material, values typical for this material type can be assumed. With E_{50}^{ref} and E_{oed}^{ref} are said to be equal, E_{ur}^{ref} is assumed to be three times greater (Seequent, 2025a).

Soft soil stiffness moduli

The stiffness parameters of the soil in the SS model are denoted with λ^* for virgin loading and κ^* for unloading and reloading (Seequent, 2025a). The parameters can be determined with the compression- and swelling indexes, C_c and C_s, and the void ratio, e. These are commonly calculated from a $log\sigma_v' - e$-graph, but as presented in a PLAXIS Bulletin from 2002 (Kant, Hutteman & Brand, 2002), the liquid limit W_L can be used to help estimate the compression- and swelling indices when no graphical data is available. The compression index can be estimated through $C_c = 1.35I_p$, where I_p is the plasticity index, which in its turn is estimated through $I_p = 0.73(W_L - 0.1)$. With this, we can express the modified compression index λ^* through:

$$\lambda^* = \frac{C_c}{(1+e)ln(10)} = \frac{1.35 * 0.73(W_L - 0.1)}{(1+e)ln(10)} \tag{4.2}$$

A similar estimation can be made for the swelling index, C_s, and can be assumed to be $C_s = \frac{I_p}{370}$ (Kulhawy & Mayne, 1990). With this, the value for the modified swelling index κ^* can be estimated to (Seequent, 2025a):

$$\kappa^* = \frac{2C_s}{(1+e)ln(10)} = \frac{2\frac{I_p}{370}}{(1+e)ln(10)} \tag{4.3}$$

Without sufficient data on the void ratio of the specific soil, an assumption of the value can be made based on the local conditions of the soil in the area. The calculated values of the stiffness parameters κ^* and λ^* are used initially in the model, before being adjusted and calibrated during the model verification process seen in Chapter 5.1.1.

4.3 PLAXIS model

To investigate the deformation behaviour associated with the excavation and sheet pile extraction, a numerical model is developed in the finite element software PLAXIS 2D. The numerical model is created based on the geometry and construction sequence presented in the full-scale field test in Chapter 3. Through staged construction analysis, the excavation, installation of structural elements, refilling, and the subsequent extraction of sheet piles are simulated. The purpose of the numerical model is to reproduce the stress redistribution and soil deformations observed during the full-scale test and evaluate various methods of modelling the sheet pile extraction. The model is built with a particular focus on the horizontal soil displacements following the sheet pile extraction and the resulting vertical displacements, causing displacements of the pipeline placed at the excavation bottom. The modelling procedure includes the definition of model geometry, assignment of constitutive soil models and material parameters, generation of mesh, and the implementation of the staged construction sequence. Different approaches for the modelling of the sheet pile extraction process are modeled and compared in order to evaluate how well it produces results similar to those observed in the Franzen & Spetz (1998) full-scale field test. The following section describes how the model is built.

4.3.1 Geometry and model boundaries

The numerical model is built with elements with 15 nodes and uses a plane-strain formulation to represent the cross-section of the excavation. This is considered appropriate due to the geometry of the trench and the constant cross-sectional conditions assumed along the length of the excavation. The model and its stratigraphy are based on the full-scale test presented in Chapter 3. The model measures 30 m wide and extends 15 m below the ground surface. These dimensions are selected to minimise the effects of boundaries on the calculated displacements. The geometry of the excavation consists of a trench with a width of 2 m and a final excavation depth of 3 m. The model also includes plate elements and anchors to represent the sheet piles, the concrete bottom slab, the struts, and the pipeline. The sheet pile plate elements are added along the excavation sides and extend 2 m beneath the excavation bottom. At two stages, struts in the shape of node-to-node anchors are installed to support the sheet piles. Furthermore, the concrete slab is placed at the excavation bottom, on top of which the pipeline is placed, both of which are modeled using plates.

The stratigraphy in the model consists of 5 soil layers, as shown in Chapter 3.2. From the ground surface, the soil profile consists of a dry crust with a thickness of 0.7 m, which is underlain by 0.8 m of clay crust. Then comes three layers of clay, on top 1.5 m of organic clay with reed, then 7 m of clay with sulfide, and finally silty clay from the depths 10 meters to 15 m. Although the bottom clay extends further down, it was deemed excessive to make the soil deeper. The global water level is set to 1.5 m depth.

The model is assigned boundary conditions to prevent rigid body motion, while allowing realistic soil deformation behaviour. The bottom boundary is restricted in both horizontal and vertical displacements, whereas the vertical boundaries are fixed only in the horizontal direction. This allows vertical displacements to happen along the model boundaries while lateral displacement is prevented on the very edges of the model. The hydraulic boundaries are closed on the sides of the model, but are set to seepage at the bottom, as the clay layer there extends further down. An overview of the numerical model is seen in Figure 4.2.

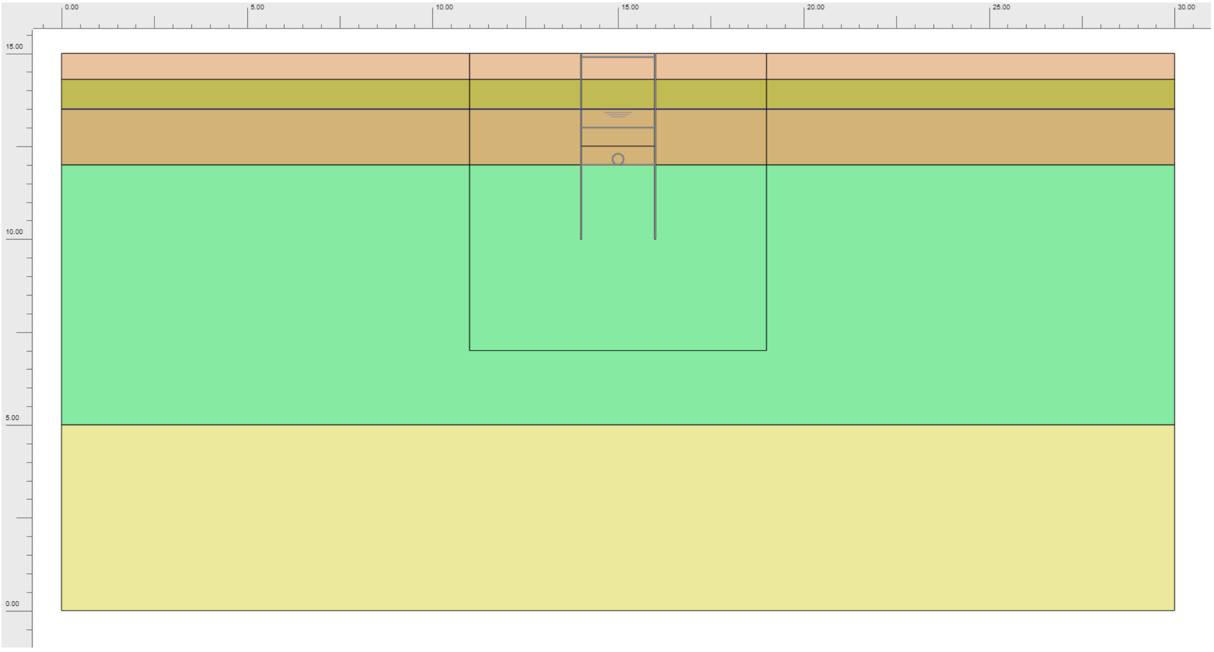

Figure 4.2: Geometry of the PLAXIS model

4.3.2 Material parameters

All initial material is presented in Table 4.1. These values have been either determined from the full-scale field test, calculated, or assumed. Certain values in the table are yet to be calibrated and can be adjusted during the calibration process.

Strength calibration

While stiffness governs the magnitude of the displacement in the soil, the strength parameters define the stability limits and the development of plastic zones. To ensure the strength parameters used in the numerical model are reflective of the local conditions at the Mölndal site, a calibration phase was conducted in the PLAXIS SoilTest tool.

The calibration process is focused on the adjustment of the effective cohesion and effective friction angle by simulating a laboratory test in PLAXIS. The chosen test for parameter calibration in this study is the direct simple shearing test (DSS). The DSS test is particularly relevant for an excavation as a sample in the SoilTest tool is subjected to simple shearing, without a large rotation of principal stress direction (VJ Tech, 2021). The stress paths experienced behind a sheet pile wall and beneath the excavation base are hence replicated with this test.

The effective cohesion, c', and effective friction angle, ϕ', are the primary driving factors of the MC failure criterion used in the MC, HS, and SS models and are of importance to be well calibrated. They are hence reconciled with the actual undrained shear strength measured in field and laboratory testing, as previously presented in Figure 3.5. To achieve

Parameter	Dry Crust	Clay Crust	Clay with reed	Clay with Sulfide	Silty Clay	Backfill bottom	Backfill top
Depth [m]	0-0.8	0.8-1.5	1.5-3	3-10	10-15	-	-
Material model	MC	MC	SS	SS	SS	HS	HS
Drainage type	Drained	Drained	Undrained A	Undrained A	Undrained A	Drained	Drained
γ_{unsat} [kN/m^3]	18.5	17.8	14.2	15.2	15.5	21	22
γ_{sat} [kN/m^3]	19,5	18.8	14.2	15.2	15.5	21	22
E'_{ref} [kPa]	30 000	5 000	-	-	-	-	-
E_{50} [kPa]	-	-	-	-	-	35 000	45 000
E_{oed} [kPa]	-	-	-	-	-	35 000	45 000
E_{ur} [kPa]	-	-	-	-	-	105 000	135 000
λ^* [-]	-	-	0.136	0.112	0.08	-	-
κ^* [-]	-	-	0.02	0.015	0.01	-	-
ν [-]	0.3	0.35	0.15	0.15	0.15	0.2	0.2
ϕ' [°]	35	32	25	26	26	38	40
ψ [°]	0	0	0	0	0	0	0
c' [kPa]	3	2	1	0	0	5	5
k_0 [-]	0.4264	0.4701	0.8120	0.6241	0.6116	0.3843	0.3572
POP [kPa]	-	-	23	15	14	-	-

Table 4.1: Initial soil properties for the PLAXIS model.

this, the shear strength profile derived from the field vane test and laboratory results served as a reference.

Within the SoilTest interface, a chosen soil type with its defined properties is used in the tool, and the known values for K_0, σ'_v, and σ'_c are used as input parameters and the test is simulated. The result shows the undrained shear strength for the clay layer. Subsequently, the effective strength parameters are iteratively tweaked until the simulated shear stress at failure in the numerical test aligns with the known undrained shear strength values. This procedure ensures that the Mohr-Coulomb failure envelope used within the more complex constitutive models captures the site-specific strength of the soil. Using the SoilTest tool reduces uncertainties regarding the relationship between the effective parameters and shear strength. Resulting strength parameters from the calibration are seen in Table 4.2. The subsequent change in the effective friction angle ϕ' results in a change of k_0, also presented in the table.

Parameter	Clay with reed	Clay with sulfide	Silty clay
ϕ' [°]	26.1	27.7	26.9
c' [kPa]	1	0	0
k_0	0.7877	0.5929	0.5890

Table 4.2: Tweaked strength parameters for clay layers.

The resulting graphs from the DSS tests for the different clay layers are seen in Appendix A.

4.3.3 Structural elements

The model features structural elements in various forms to help support the excavation. Lateral support is provided from sheet piles in the form of plate elements. The properties of the plates are made to match those of the PU12 sheet pile used in the full-scale field test. The properties of the plates are adjusted through the parameters EA and EI, the axial stiffness and the flexural stiffness, respectively. Assuming Young's Modulus E of the steel to be 210 GPa, the values of EA and EI can be calculated using values for E and I respectively (ArcelorMittal, 2026). Apart from its embedment, the sheet pile plate elements are supported by horizontal struts between the sheet piles, modeled with node-to-node anchors, the properties of which are estimated. The concrete slab at the bottom of the excavation is modeled as a plate element. Its stiffness parameters are modeled to make its equivalent thickness 70 mm, as was in the full-scale field test. Lastly, the concrete pipeline is modeled using a circular tunnel section and then assigned plate elements with properties of a concrete pipeline. Without a thickness, and only a diameter given, the thickness can only be assumed to reasonable value. Similarly, the stiffness of the concrete slab and pipeline is assumed. The given parameters for all structural elements are seen in Table 4.3.

Parameter	Sheet pile	Anchors	Concrete slab	Pipe lining
w [kN/m/m]	0.45	-	1.75	1.5
EA [kN/m]	$2.9*10^6$	10^6	$2.1*10^6$	$3*10^2$
EI [kN m^2/m]	$45*10^4$	-	860	625

Table 4.3: Properties for structural elements.

4.3.4 Mesh generation

The generated mesh in the model is refined mostly around the excavation, with particular refinement around the excavation bottom and around the sheet piles. The mesh is then coarser further away from the excavation. The model coarseness is set to medium. Altering the model coarseness to fine or coarse results in a 4.3% decrease and 3.7% increase, respectively, in the total displacements calculated at the sheet pile extraction stage. The said difference does not merit increased computational time or risk of decreased precision in the calculations. The generated mesh can be seen in 4.3.

4.3.5 Construction stages

The staged construction is divided into an initial phase followed by 11 plastic construction stages. To represent the time taken to excavate, install support, pipelines, refill and similar, each plastic stage is assigned a 1 day time interval. The different phases can be seen in Table 4.4.

The initial phase only features the original geometry with in-situ conditions of the soil. Following this, the dry crust is excavated before the sheet piles are activated, in accordance with how the full-scale test was carried out (Franzen & Spetz, 1998). The interfaces are activated for the sections where the sheet pile is in contact with the surrounding soil. With the sheet piles installed, the first strut is activated at 10 cm depth. Upon activation

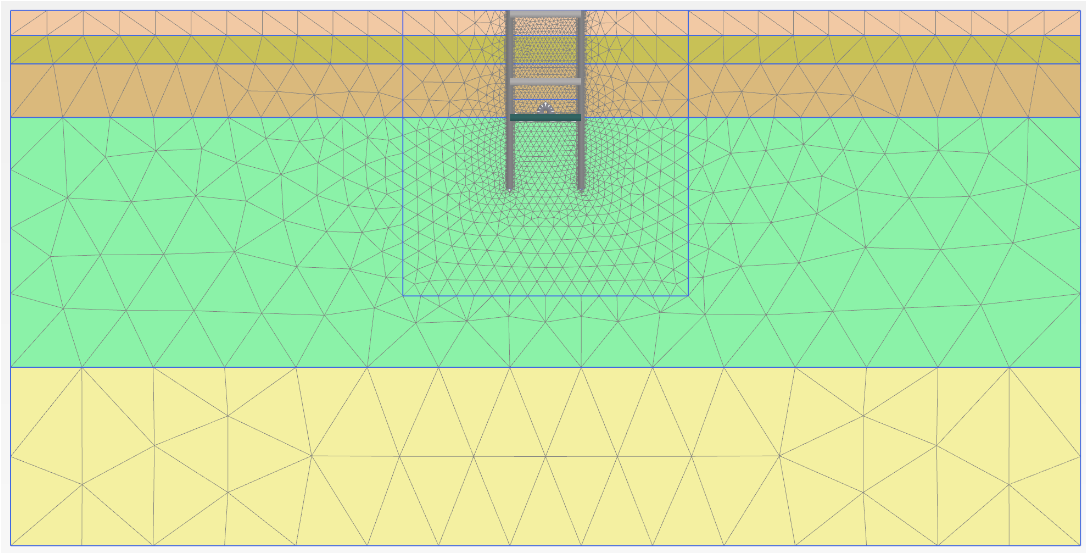

Figure 4.3: Generated mesh for the numerical model.

Nr	Phases	Calculation type	Time (total) [days]
0	Initial phase	K0-procedure	-
1	Fill excavation	Plastic	1 (1)
2	Sheet pile activation	Plastic	1 (2)
3	First strut activation	Plastic	1 (3)
4	Clay excavation	Plastic	1 (4)
5	Second strut activation	Plastic	1 (5)
6	Slab activation	Plastic	1 (6)
7	Pipeline installation	Plastic	1 (7)
8	Half refill	Plastic	1 (8)
9	Full refill	Plastic	1 (9)
10	Point fisplacement	Plastic	1 (10)
11	Sheet pile extraction	Plastic	1 (11)

Table 4.4: Phases used for modelling of the full-scale test.

of the sheet pile and the first strut, the rest of the soil is excavated down to 3 m depth, after which the second strut at 2 m depth is activated. The last support activated is the concrete slab at the bottom of the excavation. On top of the slab, the concrete pipeline is activated. Similarly to the sheet piles, the interfaces are activated as the plate elements of the concrete slab and pipeline are in contact with the surrounding soil. The trench is then refilled in two separate phases. In the same phases, the supporting struts are deactivated as the backfill carries the lateral loads from the sheet piles and the soil it retains. In order to create soil displacement which mimics that of soil adjacent to a sheet pile being extracted, an upwards point displacement of 5 cm is added to the top of both sheet piles prior to their deactivation. Through this point displacement, the sheet piles are lifted 5 cm m and create movement of the surrounding soil in an upwards direction, much like how soil is expected to behave as sheet piles are extracted. This movement of the soil is not captured through the simple deactivation of the sheet pile plate elements. Following this, the sheet piles are deactivated, and the displacements can be observed.

4.3.6 Modelling of sheet pile extraction

The soil displacement from the sheet pile extraction is modeled using four methods in four different models. All models originate from one model where the results from the stages prior to the sheet pile extraction are verified against the observed displacements in the full-scale field test. Following this stage, the model is copied and remodeled so that the various methods of sheet pile extraction are tested in separate models. The said methods and how they are implemented in the model are presented in this section.

Direct deactivation

The behaviour of the model for the sheet pile extraction without any measures to affect the displacements is done through only a deactivation of the sheet pile plate element. This is done in a separate construction stage. This action removes the lateral support and soil-structure interaction. Stresses are then redistributed, particularly near the sheet pile wall.

This method is expected to capture the stress redistribution well, but perhaps not the full displacements associated with the extraction. As the sheet pile only carries an equivalent thickness, which helps represent the stiffness of the element, its deactivation does not leave a void, and the reduction in confinement is not properly represented. Failing to create the cavity left in place of the sheet pile limits the way the surrounding soil is allowed to deform.

Volumetric strain

The volumetric strain in the model is added to a thin strip of soil along both sides of the sheet pile plate element, from surface level to a depth of 5 m. The volumetric decrease that is applied is made to be equal to that of the lost volume from the sheet pile extraction. The volumetric strain is activated in the same stage as the sheet pile plate element is deactivated. As volumetric strains of -100% can cause numerical instability, the width of the soil strips needs to be wider than that of the lost volume. Although a wide soil strip with a small volumetric strain will leave a large volume of unwanted soil. Hence, there needs to be a balance between numerical stability and realistic geometrical assumptions. Figure 4.4 shows the principles of how the soil strips deform.

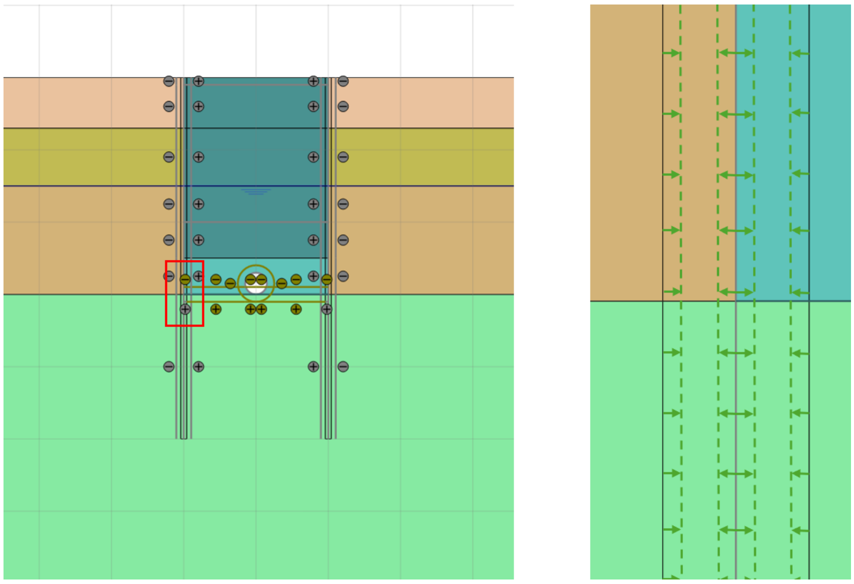

Figure 4.4: Volumetric strain applied to the soil strips on either side of the extracted sheet pile.

The sheet pile leaves a cavity with a width of 14 mm, assuming no clay sticks to its sides upon its extraction. Thus, a volume loss of 7 mm is needed per soil strip on either side of the deactivated sheet pile. Avoiding too high volumetric strains, whilst also maintaining rather slim soil strips resulted in a width of 20 mm on either side of the sheet pile and the applied strain being -35%.

Soil cluster

The soil cluster is a highly deformable soil, meant to behave almost like a void, providing little to no lateral resistance to surrounding soil. Significantly weakened soil parameters, compared to the surrounding soils, are assigned to this material. The plate element representing the sheet pile wall is deactivated in the same stage as the soil cluster activation. The activated cluster is seen in figure 4.5.

In order to allow deformations to occur as if there is a void, the width of the soil strips on each side of the sheet pile is given the width that represents half of the thickness of the sheet pile. Thus, each strip is 7 mm wide, creating a soil cluster of 14 mm total width. The cluster is activated in place of the regular soil in the extraction stage as the sheet pile is deactivated, allowing the surrounding soil to deform freely without the lateral resistance of a sheet pile supporting it. The relevant soil parameters of the cluster material are presented in Table 4.5.

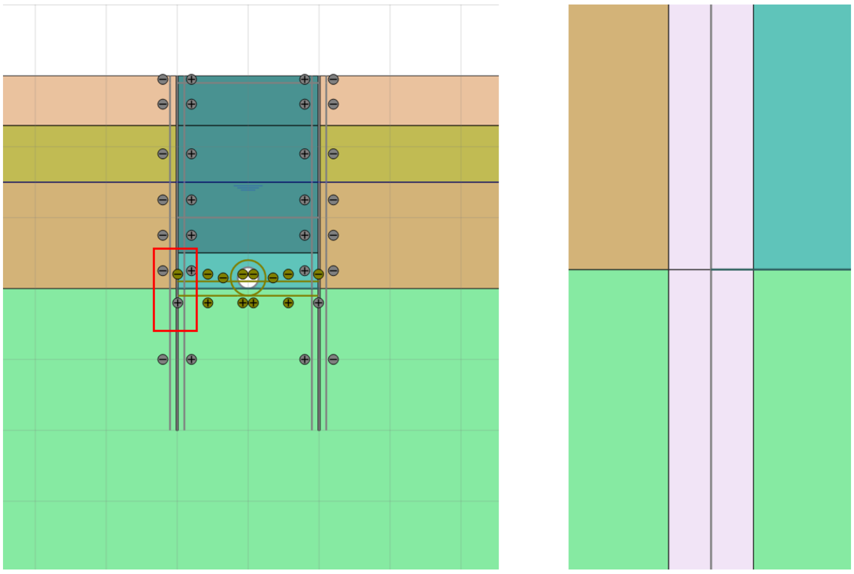

Figure 4.5: The soil cluster material applied to the soil strips on either side of the sheet pile.

Parameter	Soil Cluster
Material model	MC
Drainage type	Drained
γ_{unsat} [kN/m^2]	0.1
γ_{sat} [kN/m^2]	0.1
E'_{ref} [kPa]	10
ν [-]	0.3
ϕ' [°]	1
c' [kPa]	0.1

Table 4.5: Properties for soil clusters.

Prescribed line displacement

Similar to both the volumetric strain and the soil cluster, the prescribed line displacement is modeled using thin soil strips along the sheet piles. Along the outer lines of the soil strips, line displacements are added, facing towards the sheet pile in the middle. The activation of the prescribed line displacements is done in the same stage as where the sheet piles are deactivated. Figure 4.6 show the principles and direction of the prescribed displacements.

Much like how a volumetric strain too large relative to the thickness of the soil strip causes numerical issues, prescribed line displacements too large do too. Hence, the soil strips need to be thicker than the displacement. Numerical stability was found for soil strips with a thickness of 20 mm on either side of the sheet pile. The positive direction defined for the displacements is the right, so the left soil strip is prescribed displacements of 7 mm, and the right strip is prescribed displacements of -7 mm.

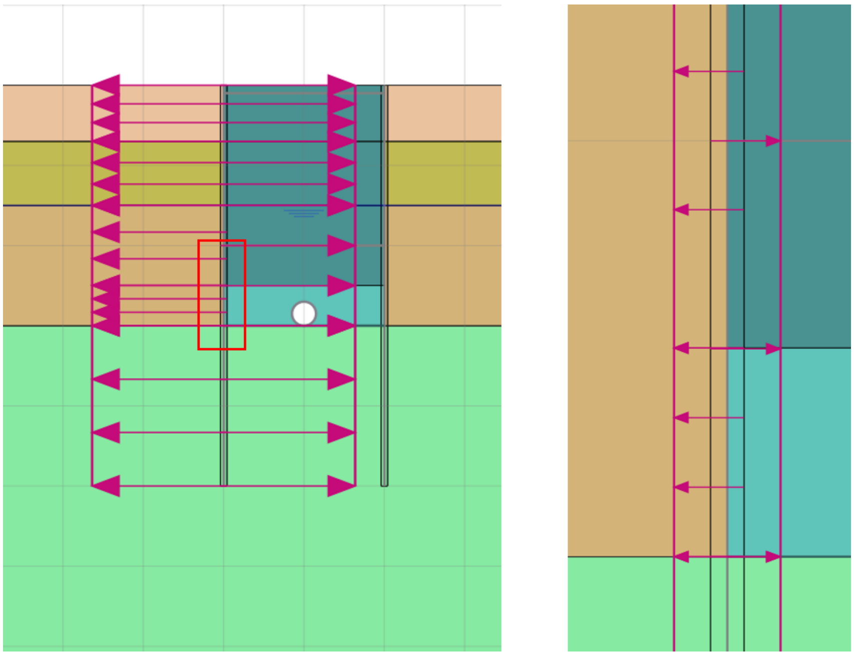

Figure 4.6: The prescribed line displacements applied to the soil strips on either side of the sheet pile.

5

Results

A numerical model was developed to investigate the effects of sheet pile extraction of pipeline settlements in soft clay. The aim of the analyses is to compare the results from numerical modelling with the observed results from the full-scale field test, to evaluate which numerical modelling method most accurately represents the extraction process and how large the associated horizontal displacements and settlements from sheet pile extraction result in.

By comparing the horizontal and vertical displacements results from the numerical model with the real-life full-scale test results for the unloading and reloading phases, verification of the numerical model can be achieved. If the numerical model shows good correspondence with the results from the observed results from the testing during said stages, the results obtained from the sheet pile extraction phase can be considered with greater confidence, as the model is more likely to represent the real soil behaviour accurately.

The result is divided into three sections: model verification, horizontal displacements, and vertical displacements. The assessment of vertical settlements is based on the observed behaviour of the horizontal displacements. The four methods presented in Chapter 4 are used to model the horizontal displacements.

The four methods are compared with the sheet pile extraction displacements from the real-life full-scale testing in order to determine which method best reproduces the behaviour observed in the full-scale field test. The method best representing the extraction process in the numerical model was subsequently chosen for the analysis of the vertical displacements.

5.1 Verification of model

In order to ensure that the model captures the behaviour of a sheet pile extraction well, it is first verified, where calculated displacements are compared to measured ones for the stages before the sheet pile extraction. Verification is done for the unloading and refilling stages, before the results are compared between the measured and calculated displacements for the sheet pile extraction. As the observed horizontal displacements start from 1.5 m depth, the calculated ones do too. As a part of the verification process, the stiffness parameters in the clay layers, as well as the unit weight of the refill material, are calibrated, the results of which are also presented in this section.

5.1.1 Parameter calibration

The heave and settlement during unloading and reloading stages are governed by the stiffness parameters of the underlying soil, which in this instance is clay, where κ^* and λ^* are the stiffness moduli. The adjusted values for the stiffness moduli are presented in Table 5.1.

Parameter	Clay with reed	Clay with sulfide	Silty clay
λ^* [-]	0.136	0.12	0.1
κ^* [-]	0.02	0.02	0.014

Table 5.1: Tweaked stiffness parameters for clay layers.

The stiffness in unloading and reloading, κ^*, is increased to amplify the settlement in reloading and heave in unloading. The stiffness in virgin loading, λ^*, is also slightly increased. The stiffness for the upper clay layer remains unchanged as it lies above the level of the excavation bottom and thus has little effect on the settling of the refill material. The unit weight of the refill material also carries significance in the magnitude of settlement following the reloading stage. The tweaked values are presented in Table 5.2.

Parameter	Backfill bottom	Backfill top
γ_{unsat} [kN/m^3]	22.1	23.2
γ_{sat} [kN/m^3]	22.1	23.2

Table 5.2: Tweaked unit weights for the coarse backfill material.

With the iteratively calibrated values, the model is verified for the unloading and reloading phases and can be used for the modelling of the sheet pile excavation stage.

5.1.2 Unloading stage

The observed as well as the calculated horizontal displacements after the excavation stage are presented in Figure 5.1.

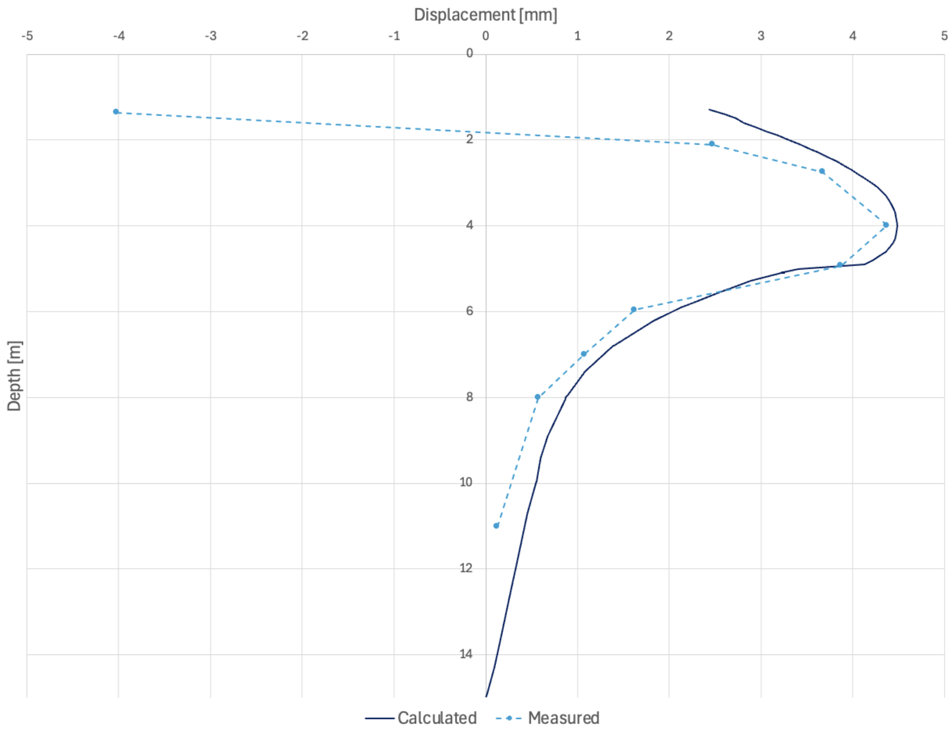

Figure 5.1: Verification of horizontal displacements for unloading phase.

In both graphs, the sheet pile wall exhibits a typical bending deformation pattern and increasing lateral displacement towards the excavation level, peaking at 4 m and then decreasing. The vertical displacements from the unloading stage during the excavation stage in the full-scale field test compared to the calculated heave from the numerical model can be seen in Figure 5.2.

5.1.3 Reloading stage

The graphs for the backfill from the full-scale field test and the numerical modelling, are presented in Figure 5.3.

During the backfill, the graphs are seen to start with displacements towards the excavation above the bottom plate and outwards underneath it. The negative peak is reached at the foot of the sheet pile a 5 m depth. The observed settlements compared to the calculated settlements for the reloading stage can be seen in Figure 5.4.

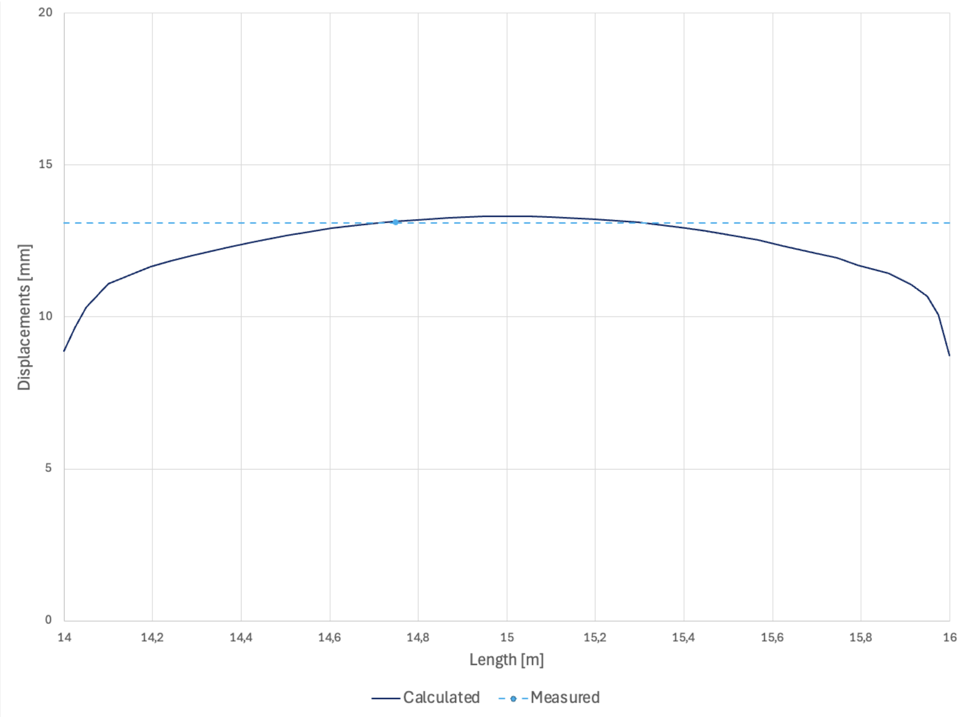

Figure 5.2: Verification of vertical displacements for unloading phase.

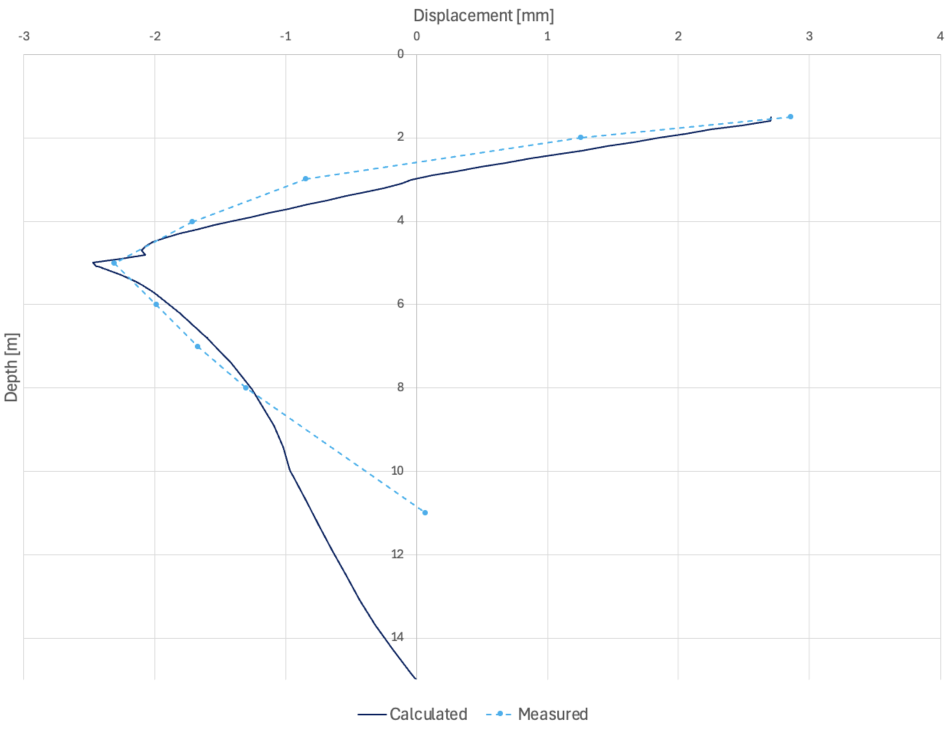

Figure 5.3: Verification of horizontal displacements for reloading phase.

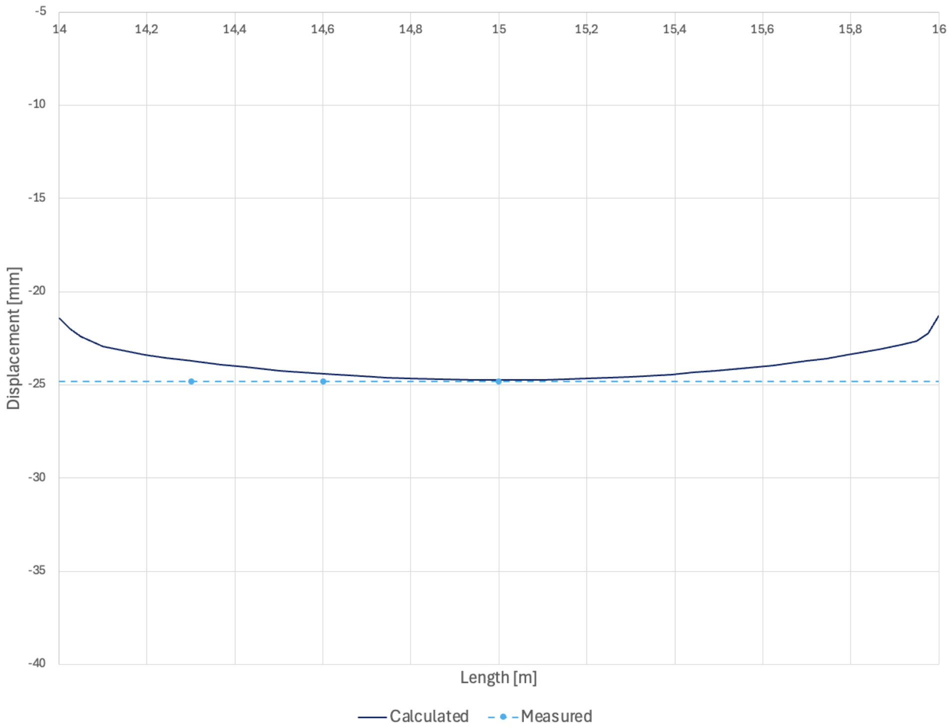

Figure 5.4: Verification of vertical settlements for reloading phase.

5.2 Sheet pile extraction

With the model verified for the stages that precede the sheet pile extraction, the methods for the modelling of this process can be evaluated and compared. The following section presents the results from the modeled method of the sheet pile extraction that best represented the observed horizontal displacements from the report presented in Chapter3. The vertical and horizontal displacements using the other modelling methods for the sheet pile extraction are presented in Appendix B. The horizontal displacements considered for the sheet pile extraction stage are those that occur between the full refill of the trench to after the extraction. The vertical displacements, however, consider the total displacements across all stages, including those that precede the sheet pile extraction. This is done for the sake of simplicity, as the results from the full-scale field test are presented in this manner.

5.2.1 Horizontal displacements

The method that best captures the horizontal displacements due to the sheet pile extraction is the method using the soil cluster with significantly weakened soil parameters. A comparison between the calculated and observed displacements using this method can be seen in Figure 5.5.

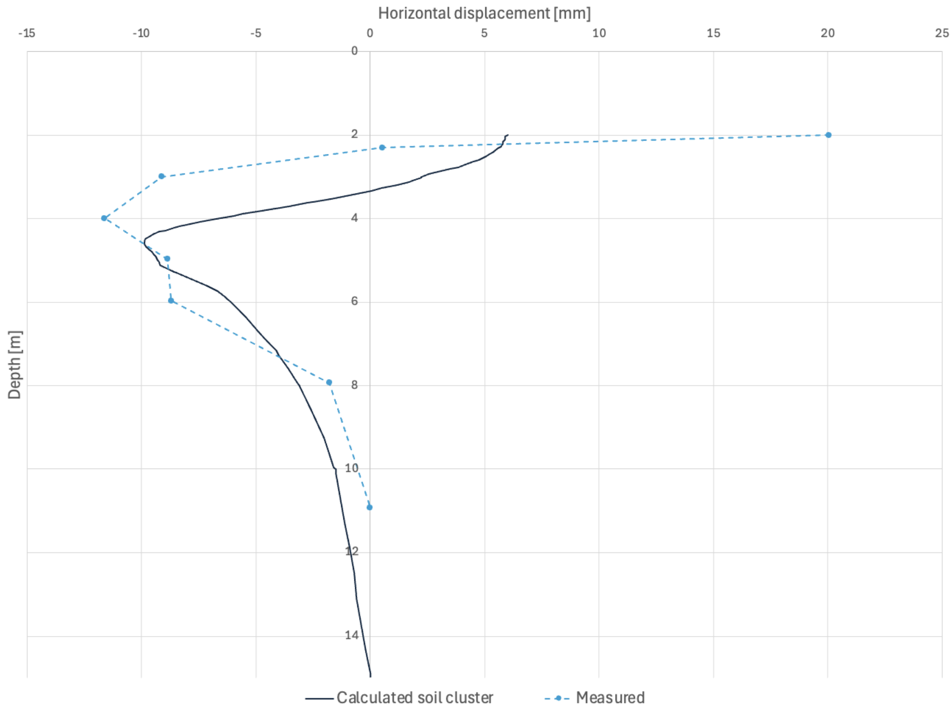

Figure 5.5: Horizontal displacements due to sheet pile extraction calculated using the soil cluster method compared to observed displacements.

5.2.2 Vertical displacements

Using the soil cluster method, the calculated settlements following sheet pile extraction are seen in Figure 5.6, where they are compared to the observed ones. This shows that the observed settlements are larger than those observed in the numerical modeling. The settlements are largest in the middle of the excavation, which corresponds to 15 meters in the figure 5.6.

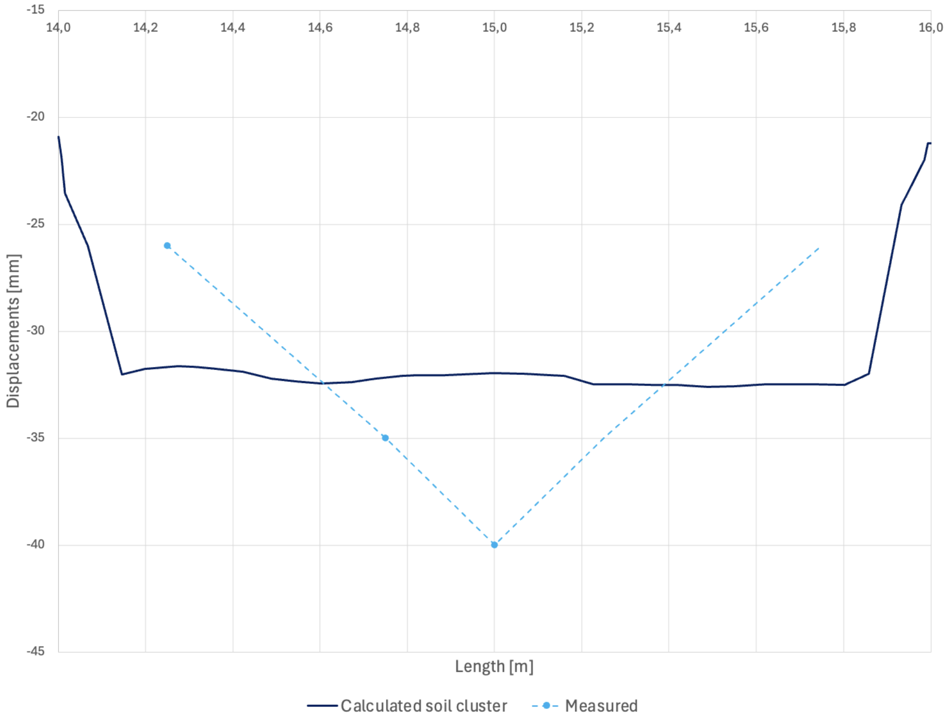

Figure 5.6: Total vertical settlement after sheet pile extraction calculated using the soil cluster method compared to observed settlement.

5.2.3 Observed void backfilling following sheet pile extraction

Displacement vectors are a tool in PLAXIS Output window, which showcases the displacement direction and magnitude. Figure 5.7 illustrates the soil displacements obtained from the numerical modelling during the extraction phase of the sheet pile wall.

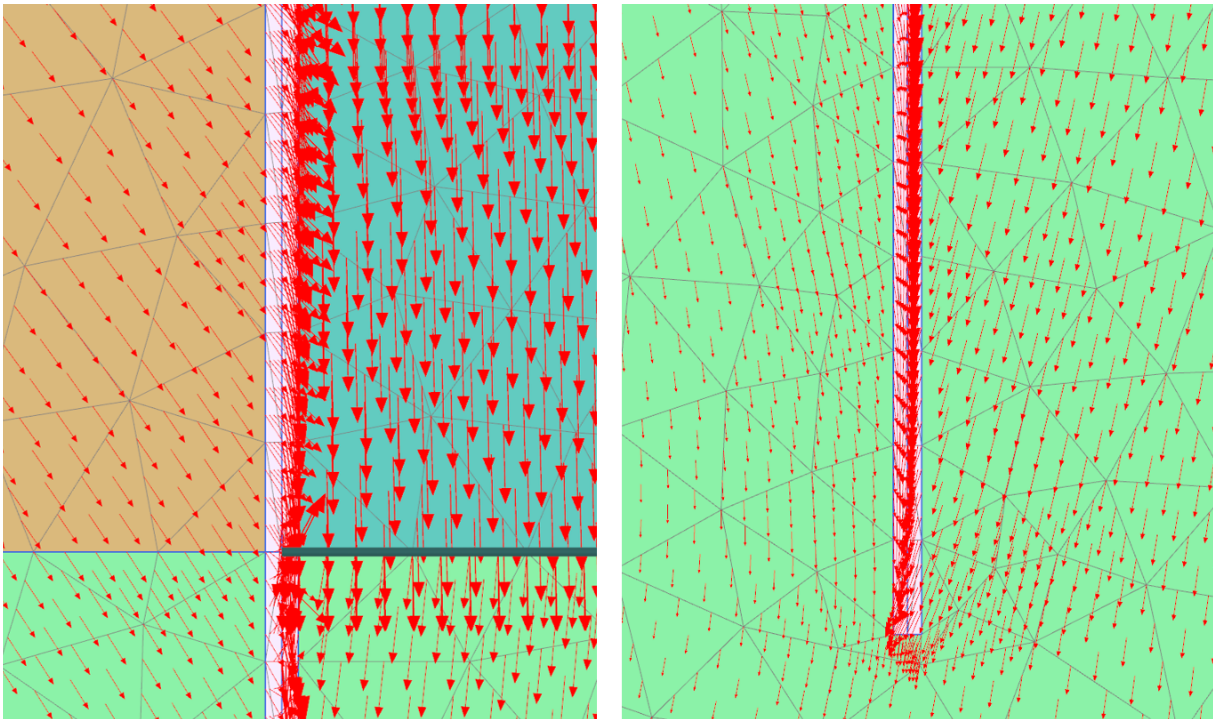

Figure 5.7: Displacement vectors showing magnitude and direction of displacement from sheet pile extraction around excavation bottom (left) and at the foot of the sheet pile (right).

The vectors in the figure show that the displacement of the soil differs above and below the excavation bottom. Above the excavation bottom, as can be seen in the figure furthest to the left, the displacement vectors indicate that the soil from the outside of the excavation moves towards the void created by the extracted sheet pile. Below the excavation bottom, as can be seen in the figure to the left, indicates the displacement vectors that the soil tends to move from the excavation side towards the outside.

5.3 Sensitivity analysis

In order to test the sensitivity of the model, adjustments are made to the parameters of the refill material, where the strength and stiffness parameters are mostly assumed. Two cases are tested, where the stress and stiffness are increased in one case and decreased in another. The altered parameters for strength and stiffness are seen in Table 5.3.

With the adjusted parameters, the horizontal and vertical displacements are calculated for the sheet pile extraction stage and compared to the results calculated for the initially assumed values. The horizontal phase displacements are seen in Figure 5.8.

	Decreased		Increased	
Parameter	Backfill bottom	Backfill top	Backfill bottom	Backfill top
ϕ' [°]	29	30	47	50
E_{50} [MPa]	18	20	54	60
E_{oed} [MPa]	18	20	54	60
E_{ur} [MPa]	54	60	162	180

Table 5.3: Stiffness and strength used to test sensitivity for the coarse backfill material.

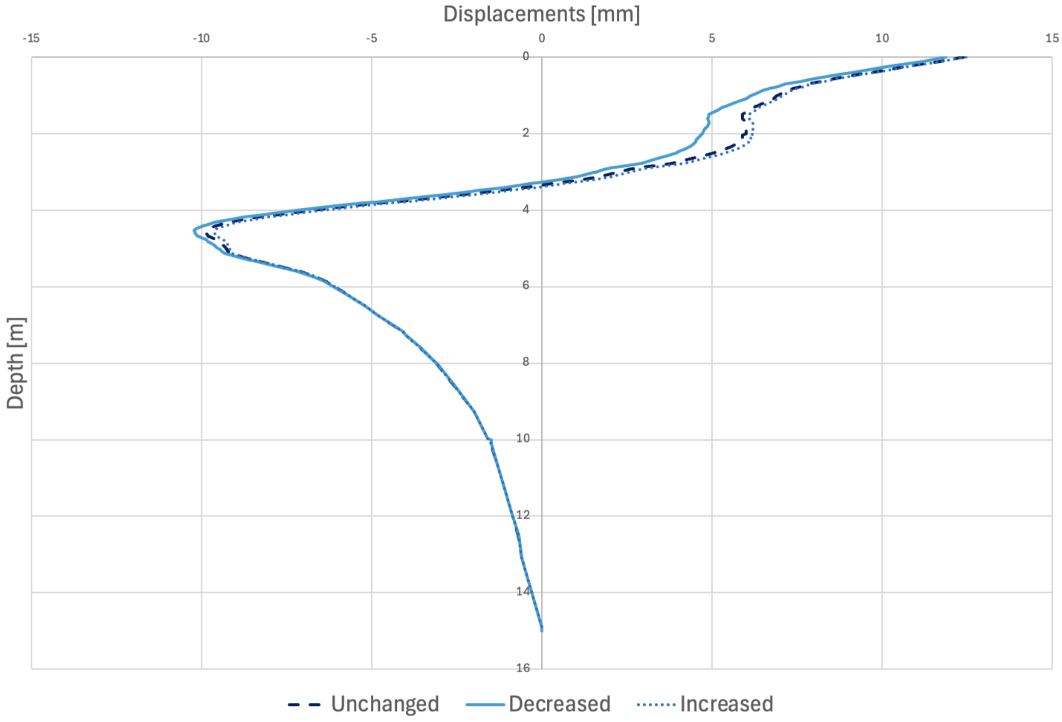

Figure 5.8: Change in horizontal displacements from the sheet pile extraction stage for different strength and stiffnesses for the backfill material.

The results show how both an increase and a decrease in the stiffness and strength of the refill material result in small changes to the horizontal displacements from the sheet pile extraction. The difference is most significant around 2 m depth and around the peak between 4 and 5 m depth. The total vertical displacements after the sheet pile extraction are presented in Figure 5.9.

The vertical settlements following the sheet pile extraction show that an increase in stiffness and strength causes a settlement decrease of 2 mm, whilst a decrease has little to no effect.

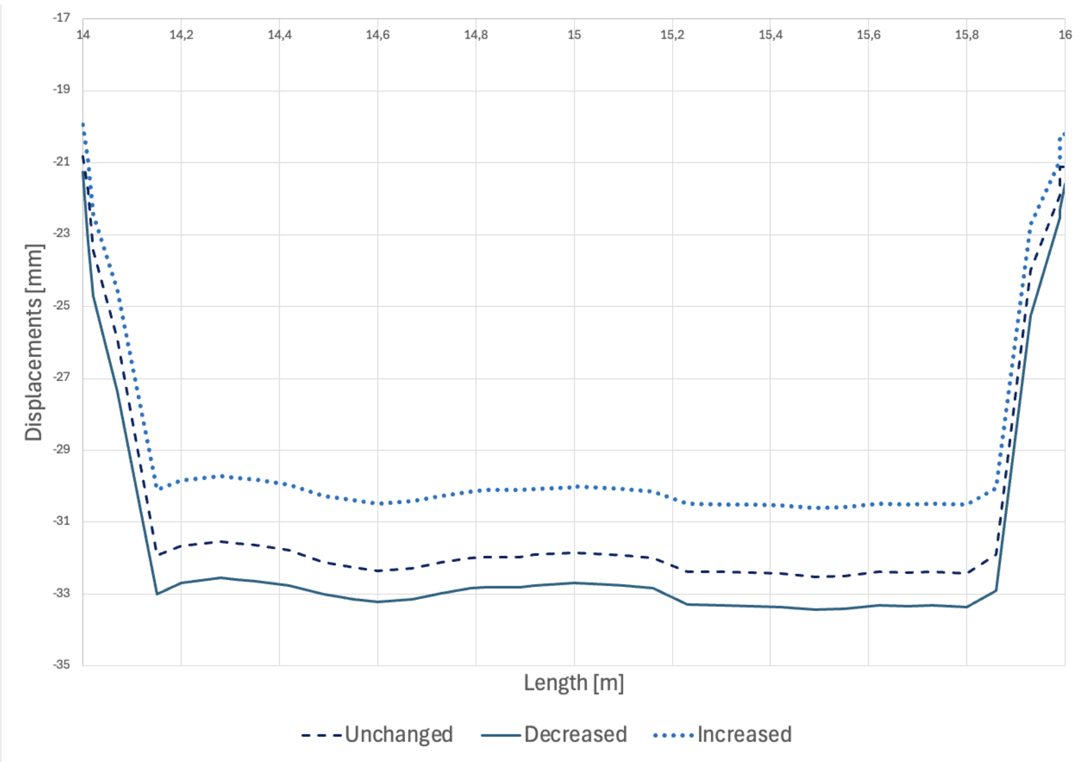

Figure 5.9: Change in vertical displacements after the sheet pile extraction for different strength and stiffness for the backfill material.

6

Discussion

This chapter discusses the different components of the project and discusses the various factors that influenced the obtained results. The development of the model and its limitations are discussed and evaluated. Here, both the initial stages, which are part of the model verification, and the different sheet pile extraction methods are considered here. The resulting horizontal displacements of the soil of the sheet pile extraction, as well as the subsequent vertical displacements are discussed and evaluated in this chapter. Finally, the key limitations of the report and their implications on the results are discussed and recommendations for further work are presented.

6.1 Reliability of the numerical model

The numerical model was able to reproduce the general displacement behaviour observed in the full scale field test during both excavation and reloading. Although discrepancies remained between the calculated and observed values for the sheet pile extraction, the result was considered satisfactory when using the method with the soil cluster with significantly reduced stiffness and strength soil parameters.

The purpose of the model verification was not only to calibrate certain parameters governing heave and settlement in unloading and reloading, but also to determine whether the model could capture the mechanisms responsible for soil movement during the excavation process. As the verification process demonstrated that the model captured the mechanisms governing both horizontal and vertical soil displacements, it can be considered successful. As the soil parameters governing the heave and settlement were calibrated, the results were more precise and greater confidence could be put into the model recreating the displacements occurring during the sheet pile extraction as well. When sensitivity was tested for the backfill material, the model showed relatively low sensitivity, which further increases confidence that the result is not only based on a combination of soil parameters, but also that the general behaviour is governed by broader model mechanisms.

However, the successful verification should be interpreted with some caution. Agreement between calculated and observed results does not automatically imply that other mechanisms are recreated well by the model, such as that of the sheet pile extraction. For this, the behaviour is less understood than the heave and settlement for unloading and reloading. So while the verification increases confidence in the model, uncertainties remains regarding how accurately the model represents the processes governing closure of the void and the stress redistribution following the sheet pile extraction. The calculated results of the extraction should therefore be regarded as a reasonable approximation of the field behaviour rather than an exact prediction.

6.2 Interpretation of sheet pile extraction behaviour

The results when using the various modeling methods for the sheet pile extraction show that the chosen modeling approach has a significant influence on the calculated soil displacements. While all methods used generated stress redistribution in the surrounding soil, their respective ability to reproduce the observed horizontal displacements varied considerably. Only the soil cluster method produced horizontal displacements that resembled those observed in the field test.

The simple deactivation of the sheet pile plate element underestimated the observed displacements. This indicates that the removal of structural support provided by the sheet pile without modelling of the void is not sufficient to recreate the displacements from the sheet pile extraction. If only the stress redistribution from the sheet pile deactivation governed the displacements, the calculated results would be closer to the observed ones.

The volumetric strain method generated displacements similar to those observed in the field test, but underestimated their magnitude. The way the cavity was generated, where a total of 40 mm width was reduced to 25 mm and excess soil was left between the created voids, likely affected the the resulting displacement mechanisms and limited the movement of the surrounding soil into the void. This implies that not only the magnitude of the volume loss, but also the geometry of that volume loss influences how stressed are redistributed and how soil deforms.

A similar observation can be made for the prescribed line displacement, where the same volume loss is generated as the volumetric strain, but how the volume loss occurs and the geometry of it differs from the soil cluster method. This strengthens the idea that the displacement behaviour is not solely governed by the amount of volume removed, but also how that volume loss is introduced into the model. Boundary movements in the prescribed displacement method creates a different stress redistribution than the other methods, where soil displacement patterns are different and not representative of those observed in the full scale field test.

The soil cluster method provides the best agreement with the observed displacements. By introducing a highly deformable zone with the same width as the extracted sheet pile, the method allowed the surrounding soil to move towards the voil in a manner that closely resembled the observed behaviour. Unlike the other methods tested, the soil cluster represented the extracted sheet pile as a single continuous deformable zone with the same width as the removed sheet pile. This allows the surrounding soil to deform towards one concentrated zone, creating displacement patterns more consistent with the observed behaviour. This result indicates that accurately representing the geometry of the void left after the sheet pile was extracted is important.

However, the soil cluster method should still be interpreted carefully, as it does not create a true cavity, unlike two of the other methods. The low stiffness material in the soil cluster remains in the model and is displaced rather than removed. Therefore, the agreement between the calculated and observed results should not necessarily be interpreted as evidence that the physical extraction process is fully represented, rather it indicates that the resulting stress redistribution and deformation pattern resemble those observed in reality for this specific case. The distinction is important, as it highlights the difference between reproducing observed behaviour and accurately modelling the physical mechanism responsible for it.

Considering the results of these methods, the sheet pile extraction should be viewed as a volume-loss problem, rather than just a support-removal problem. However, consideration should be taken as to how that volume loss is modelled and the surrounding soil is allowed to deform.

6.3 Vertical displacements due to sheet pile extraction

As described above, the vertical displacements during the unloading and reloading phases have been calibrated to show good agreement between the full-scale field test and the numerical modelling. However, the vertical displacements from the numerical modelling during the sheet pile extraction are smaller at the sheet pile extraction phase than those observed in the full-scale field test. As presented in the results, the total vertical settlement observed by Franzen & Spetz (1998) was 40 mm, including all phases, while the numerical modelling predicted a total settlement of 33 mm.

If using the ground surface as the reference point and looking at Figure 5.6 and Figure 5.3, it can be seen that the reloading phase corresponds to 63% or 25 mm of the total settlements. If looking at figure 5.6 it can be seen that the numerical modeling underestimates the settlements with 8 mm in comparasion with the full-scale field test.

One possible explanation for the larger settlements observed in the full-scale field test could be that the real-life full-scale test is affected by many factors not included in the numerical modelling. These factors may include vibrations during installation and extraction of the sheet pile, changes in groundwater levels, workmanship-related disturbances at the excavation bottom, to name a few. Implementing these effects in the numerical model was seen as too complex within the scope of this project. But since the sheet pile extraction, and only the sheet pile extraction is simulated and modelled in the numerical modelling, if the settlements from the numerical modeling is subtracted from the case study, it could be concluded that the sheet pile extraction corresponds to 20% of the total settlements while disturbances corresponds to 17% of the total settlements.

6.4 Observed void backfilling following sheet pile extraction

The displacement vectors from the numerical modelling in PLAXIS 2D provide insights into how the void created by the sheet pile extraction of the sheet pile is filled. The results show that the backfilling is not uniform with depth, and instead showing that it depends on whether the soil is located above or below the excavation bottom.

Above the excavation bottom, the displacement vectors show that the soil outside the excavation moves towards the void generated by the sheet pile extraction. This soil displacement corresponds to the reduction in lateral support that occurs when the sheet pile is extracted. As a result of the reduction in lateral support, the soil outside the excavation tends to move towards the newly created void because of the relatively high horizontal stresses. The horizontal displacements calculated by the numerical model support this interpretation, as it shows inward soil displacements in the soil layers above the excavation bottom.

Below the excavation bottom, the displacement vectors show opposite behaviour. The soil from the excavation side moves towards the void left by the extracted sheet pile. One possible explanation is that there is a redistribution of stresses that is caused by the excavation, which has already mobilized soil displacements around the section of sheet pile wall. When the sheet pile is extracted, the stress around the embedded sheet pile results in soil moving from the excavation side towards the void.

This interpretation of the calculated results is further supported by a simple volume consideration. The sheet pile wall occupies approximately 0.014 m of width per meter along its entire depth of 5 meters, which must be filled after extraction. Assuming that the entire void is filled only with soil originating from within the excavation and that no volume change occurs during the process, the resulting volume loss would correspond to 70 mm of settlement at the ground surface. However, the numerical modelling results predict settlements of a maximum of 40 mm. This indicates that the void cannot entirely be filled with soil from within the excavation. The volume reasoning, therefore, supports the displacements presented in figure 5.7. A portion of the material that fills the void generated from the sheet pile extraction must originate from the outside of the excavation. The excavation bottom or hence, change in material, appears to act as a transition level separating soil displacements.

Consequently, the results indicate that the void above the excavation bottom is filled primarily with material from the outside, whereas the void below the excavation bottom is filled with material moving from within the excavation. This interpretation provides an explanation for both the calculated displacement vectors and the observed settlements following the sheet pile extraction.

6.5 Vertical displacements under pipeline

During sheet pile extraction, it would be reasonable to expect most of the settlements to occur adjacent to the sheet pile, since the volume loss caused by the extraction creates a void that must be filled with material from the closest surrounding area. However, this is not the case in either the full-scale field test or the numerical modelling.

One possible explanation for the larger settlements observed at the pipeline location compared to those adjacent to the sheet pile is described by Franzen & Spetz (1998) when discussing the results of the full-scale field test. They mention that the difference in stiffness between the pipeline and the surrounding soil could cause this. During the extraction phase of the sheet pile, the soil inside the excavation loses its lateral support and temporarily acts as a wide, unsupported excavation. Therefore, because of the relatively high stiffness of the pipeline, a significant portion of the load above is transferred vertically beneath the pipeline. This creates a concentration of stresses below the pipeline, which contributes to the settlements observed near the center of the excavation.

6.6 Limitations and uncertainties

Several uncertainties regarding the project have been declared earlier in the discussion, including, but not limited to, simplified modelling assumptions, material parameters in the soil models, no consolidation considered, the need for further sensitivity analysis, as well as assumptions during the interpretation of the results from the full-scale field test due to uncertainties in the observed results.

The main uncertainties of the report lie in the very problem evaluated in the report—the sheet pile extraction. Furthermore, the modelling of the sheet pile installation also carries uncertainties. Assumptions and simplifications around the model can be made, but many factors that could prove to make a difference to the calculated results are not included in the numerical model. The installation of the sheet pile is modeled through a simple activation of the plate element, meaning that no soil displacement or stress redistribution is captured during this stage. The stress increase during the installation and subsequent stress release during the extraction, are not included in the numerical model. For the extraction, only the void left by the sheet pile is modeled, and the effects from the compaction due to vibratory sheet pile extraction are disregarded. This was deemed too advanced to consider and would ultimately lead to further uncertainties around the model.

6.7 Recommendations for future research

Future research is recommended to investigate the procedures currently listed as limitations of this study. It should aim to quantify the settlements that the numerical model did not capture from the sheet pile extraction. Furthermore, in addition to testing the applicability of the chosen method in this report, an investigation into how different conditions may affect the result should be conducted. Different conditions include sheet pile dimensions, different soil conditions, and installation procedures.

7

Conclusion

This study investigates how the void left in place of a sheet pile upon its extraction from a backfilled excavation trench in soft soil can be modelled using the numerical modelling software PLAXIS 2D. The following conclusions can be drawn from the study:

- The study has concluded that the best modelling approach for the extraction of the sheet pile was the method using a soil cluster, where a soil with significantly weakened soil parameters is used to represent the void of the extracted sheet pile.

- Although significant additional settlements are contributed by the extraction of the sheet pile using the soil cluster method, it does not account for all vertical settlements and cannot fully account for the difference in settlement across the excavation bottom.

- The calculations indicate that the void left by the sheet pile following the sheet pile extraction is filled largely by the clay outside the excavation for depths above the excavation bottom, and from the clay underneath the excavation base at levels beneath it, due to the heavy overlaying refill material.

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A

Appendix

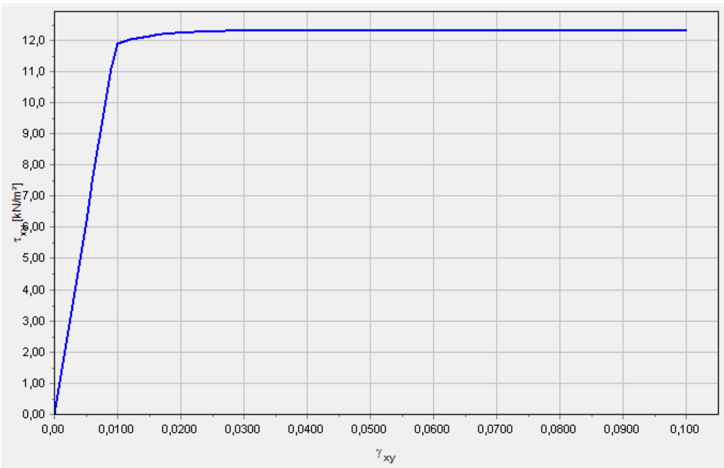

Figure A.1: Shear strength graph in DSS test in SoilTest tool for Clay with reed.

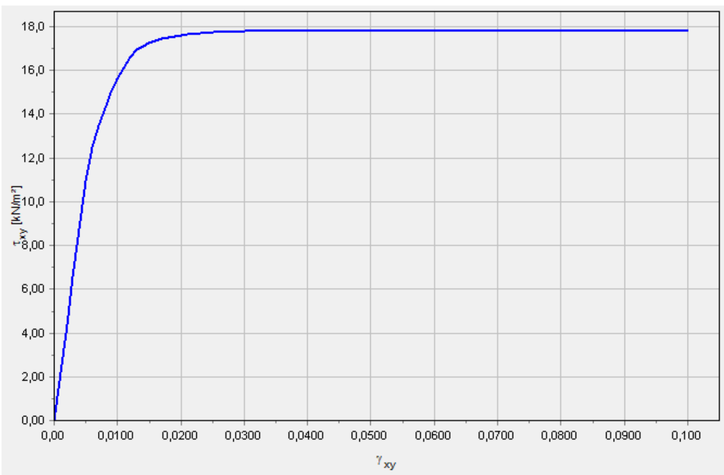

Figure A.2: Shear strength graph in DSS test in SoilTest tool for Clay with sulfide.

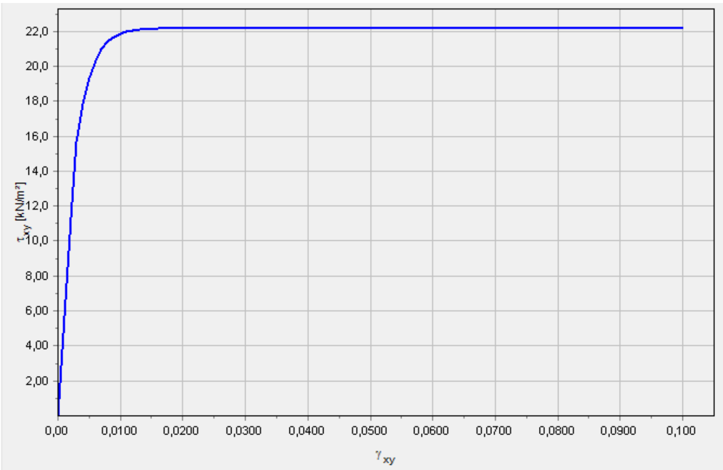

Figure A.3: Shear strength graph in DSS test in SoilTest tool for Silty clay.

B

Appendix

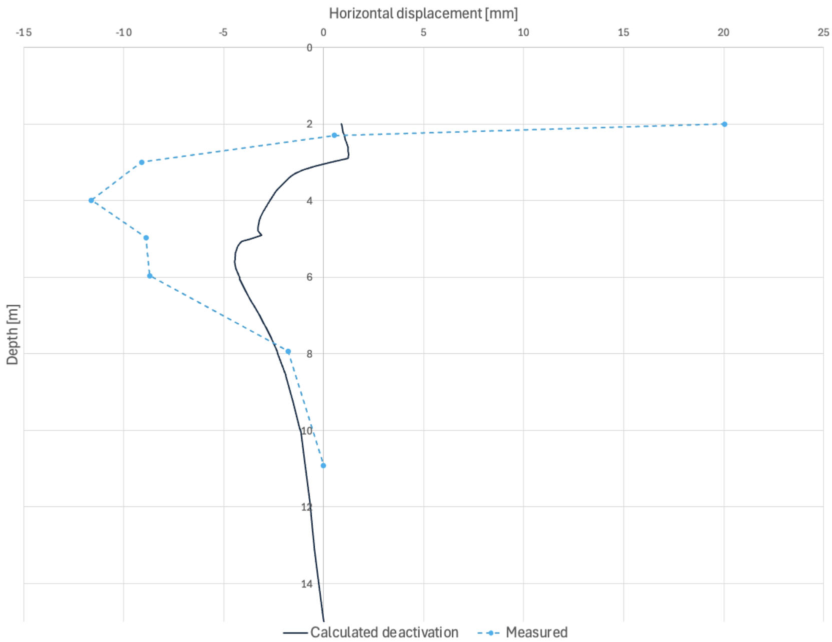

Figure B.1: Modeled total horizontal deformations after the sheet pile extraction with the deactivated sheet pile.

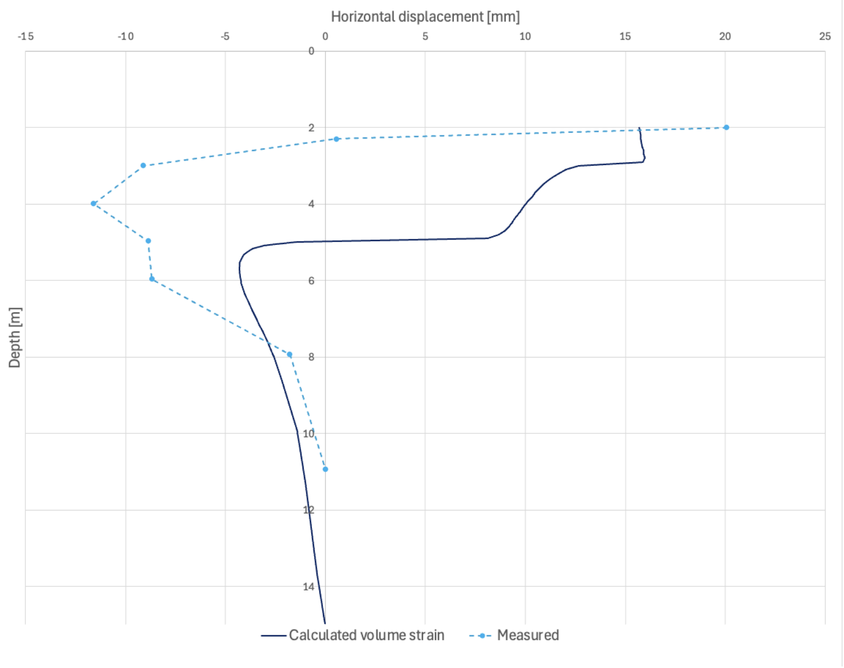

Figure B.2: Modeled total horizontal deformations after the sheet pile extraction with the imposed volumetric strain.

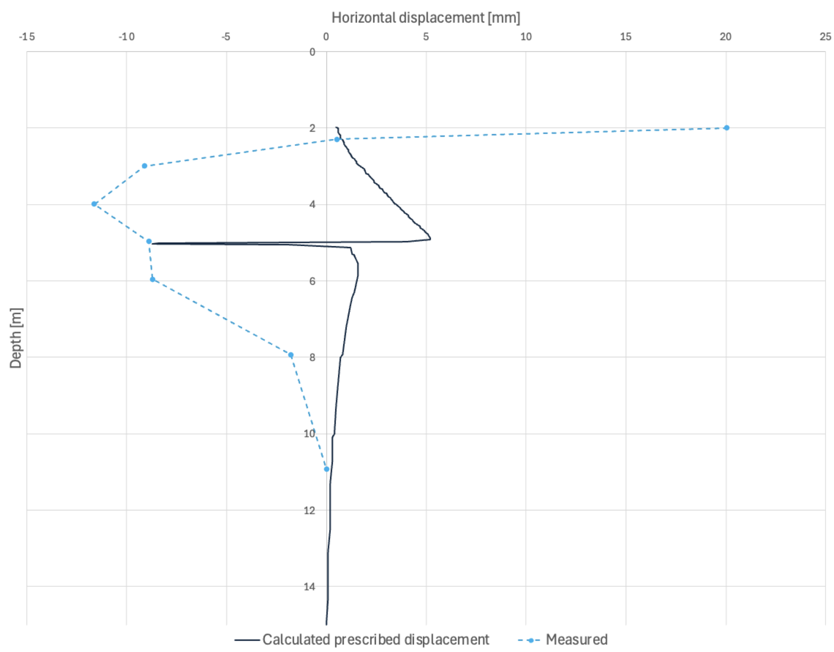

Figure B.3: Modeled total horizontal deformations after the sheet pile extraction with the prescribed line displacements.

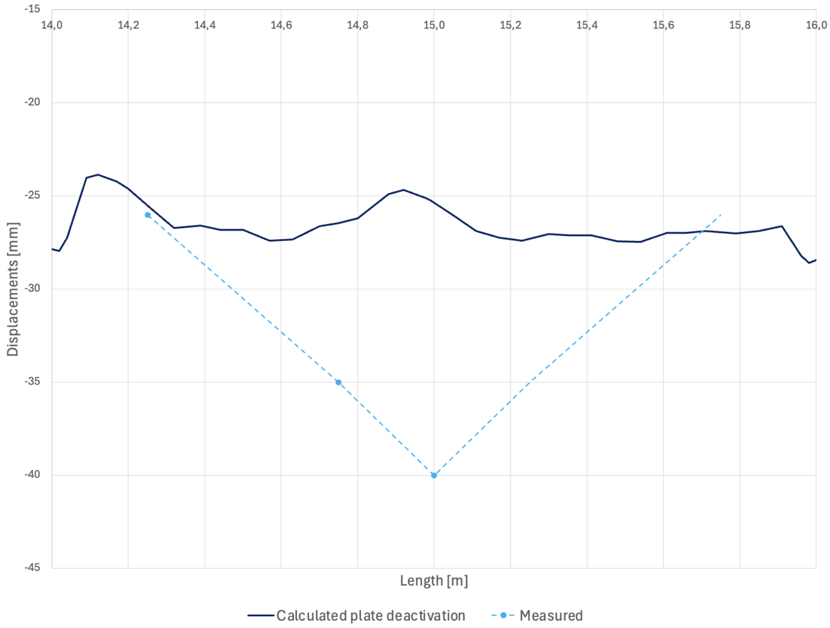

Figure B.4: Modeled total vertical deformations after the sheet pile extraction with the deactivated sheet pile.

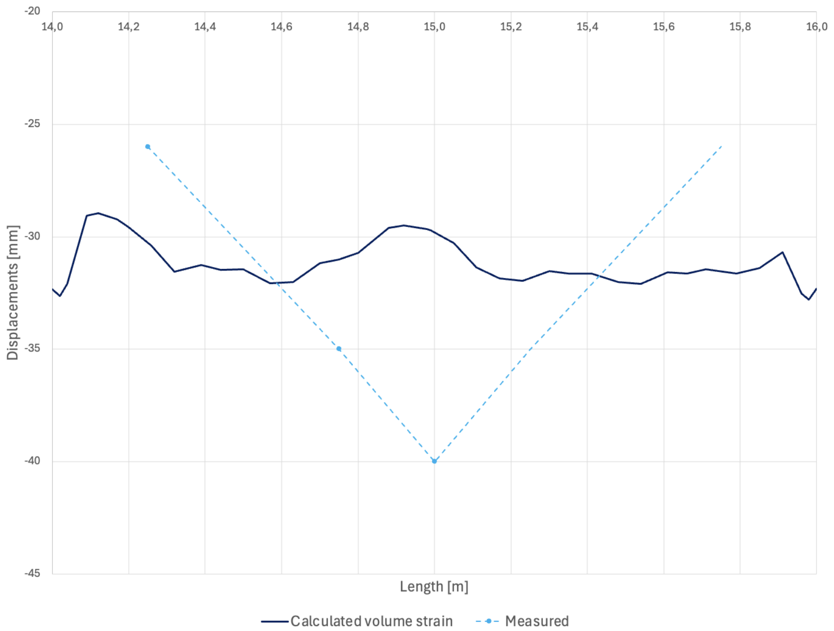

Figure B.5: Modeled total vertical deformations after the sheet pile extraction with the imposed volumetric strain.

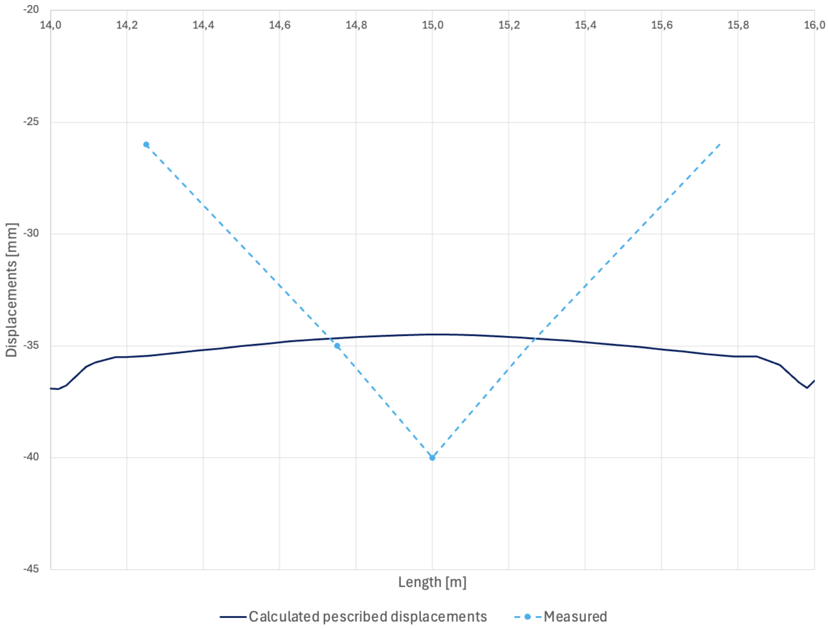

Figure B.6: Modeled total vertical deformations after the sheet pile extraction with the prescribed line displacements.